US009551552B2

(12) **United States Patent**
**Kolanek et al.**

(10) **Patent No.: US 9,551,552 B2**
(45) **Date of Patent: Jan. 24, 2017**

(54) **METHODS AND APPARATUSES FOR AERIAL INTERCEPTION OF AERIAL THREATS**

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(73) Assignee: **Orbital ATK, Inc.**, Plymouth, MN (US)

( * ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 977 days.

(21) Appl. No.: **13/839,637**

(22) Filed: **Mar. 15, 2013**

(65) **Prior Publication Data**

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**Related U.S. Application Data**

(63) Continuation-in-part of application No. 13/455,831, filed on Apr. 25, 2012, now Pat. No. 9,170,070.

(Continued)

(51) **Int. Cl.**

*F41G 7/34* (2006.01)
*F42B 10/66* (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ................. ***F41G 7/34*** (2013.01); ***F41G 7/007*** (2013.01); ***F41G 7/303*** (2013.01); ***F41H 11/02*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC .......... G05D 1/08; G05D 1/0808; G05D 1/10; G05D 1/107; F41H 11/02; F41G 7/007; F41G 7/20; F41G 7/30; F41G 7/301; F41G 7/303; F41G 7/34; F41G 7/343; F42B 10/60; F42B 10/66; F42B 10/661;F42B 10/663; F42B 10/665; F42B 10/666; F42B 10/668; F42B 15/01; F42B 15/10; F42B 15/105; F02K 9/80; F02K 9/84; F02K 9/86; F02K 9/88

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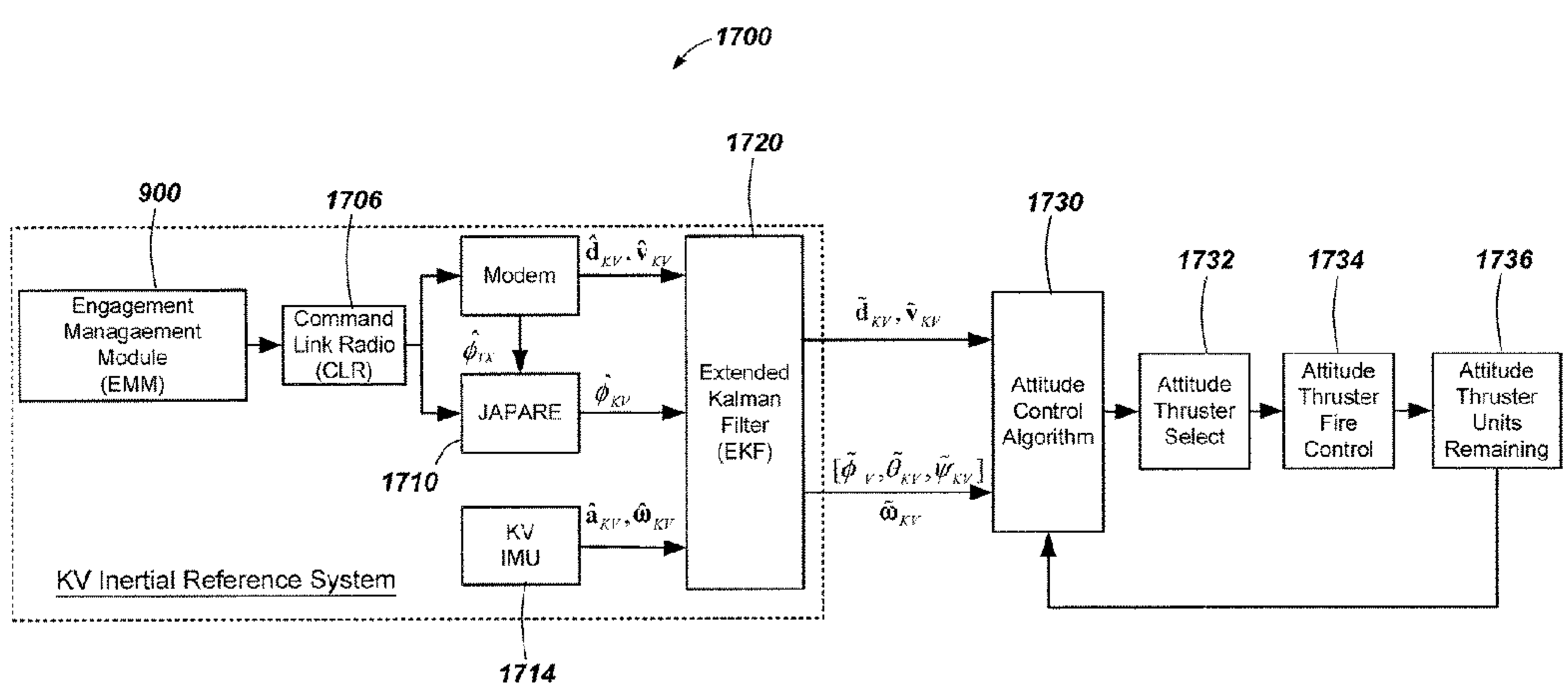
*Primary Examiner* — Bernarr Gregory
(74) *Attorney, Agent, or Firm* — TraskBritt

(57) **ABSTRACT**

Embodiments include active protection systems and methods for an aerial platform. An onboard system includes radar modules, detects aerial vehicles within a threat range of the aerial platform, and determines if any of the aerial vehicles are an aerial threat. The onboard system also determines an intercept vector to the aerial threat, communicates the intercept vector to an eject vehicle, and causes the eject vehicle to be ejected from the aerial platform to intercept the aerial threat. The eject vehicle includes alignment thrusters to rotate a longitudinal axis of the eject vehicle to substantially align with the intercept vector, a rocket motor to accelerate the eject vehicle along an intercept vector, divert thrusters to divert the eject vehicle in a direction substantially perpendicular to the intercept vector, and attitude control thrusters to make adjustments to the attitude of the eject vehicle.

**45 Claims, 24 Drawing Sheets**



**Related U.S. Application Data**

(60) Provisional application No. 61/606,010, filed on Mar. 2, 2012.

(51) **Int. Cl.**

| | |
|---|---|
| ***F42B 15/01*** | (2006.01) |
| ***F41G 7/00*** | (2006.01) |
| ***F41H 11/02*** | (2006.01) |
| ***F41G 7/30*** | (2006.01) |
| ***F42B 15/10*** | (2006.01) |
| ***G05D 1/08*** | (2006.01) |
| *F42B 10/00* | (2006.01) |
| *F42B 15/00* | (2006.01) |

(52) **U.S. Cl.**
CPC ............... ***F42B 10/66*** (2013.01); ***F42B 15/01*** (2013.01); ***F42B 15/105*** (2013.01); ***G05D 1/0808*** (2013.01)

(58) **Field of Classification Search**
USPC .................................................... 244/3.1–3.3
See application file for complete search history.

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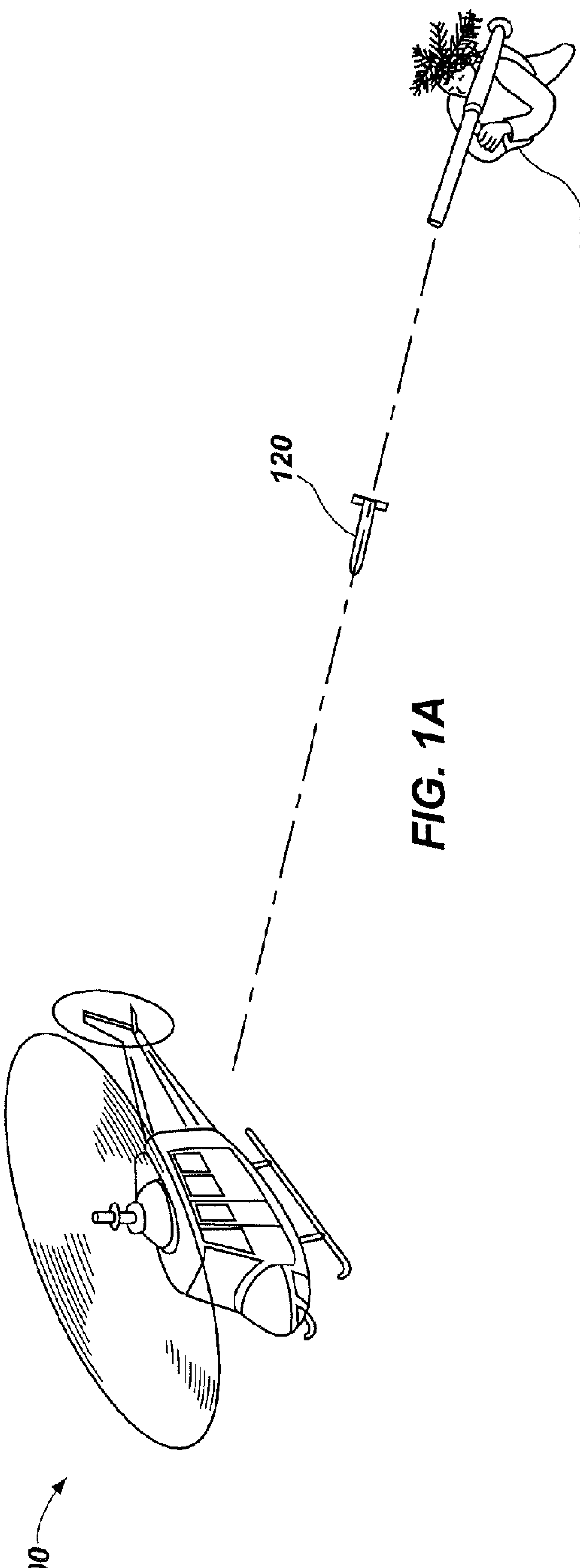



FIG. 1A

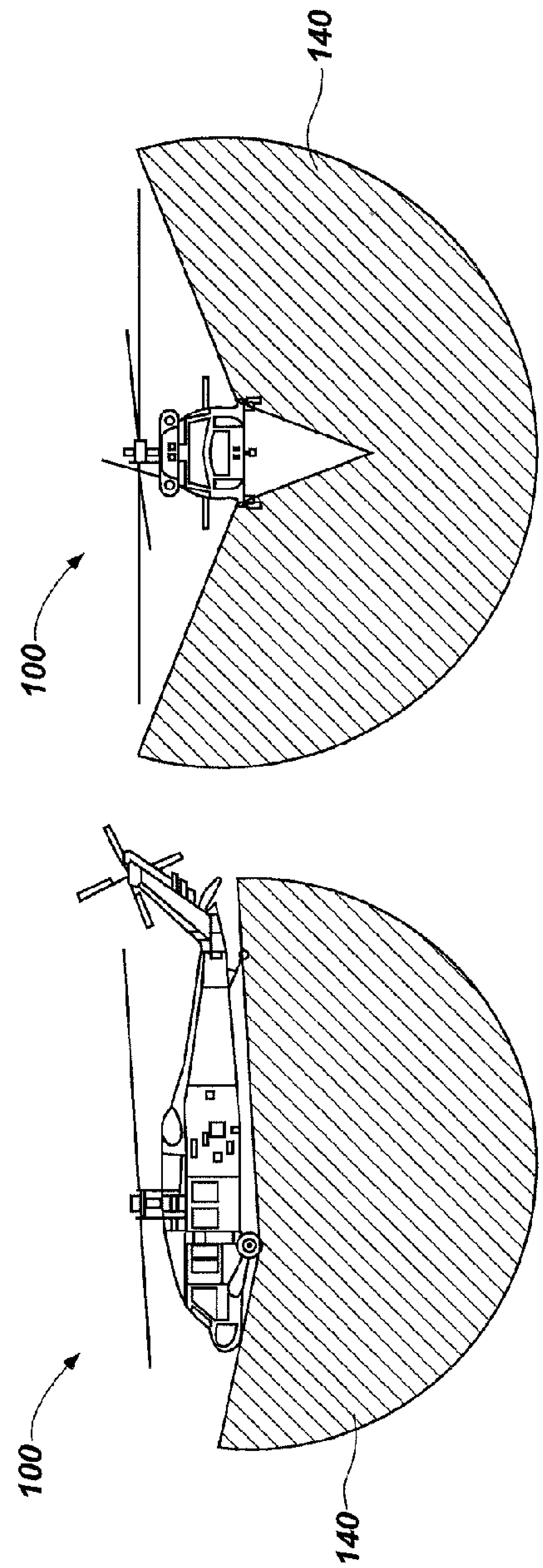



FIG. 1B

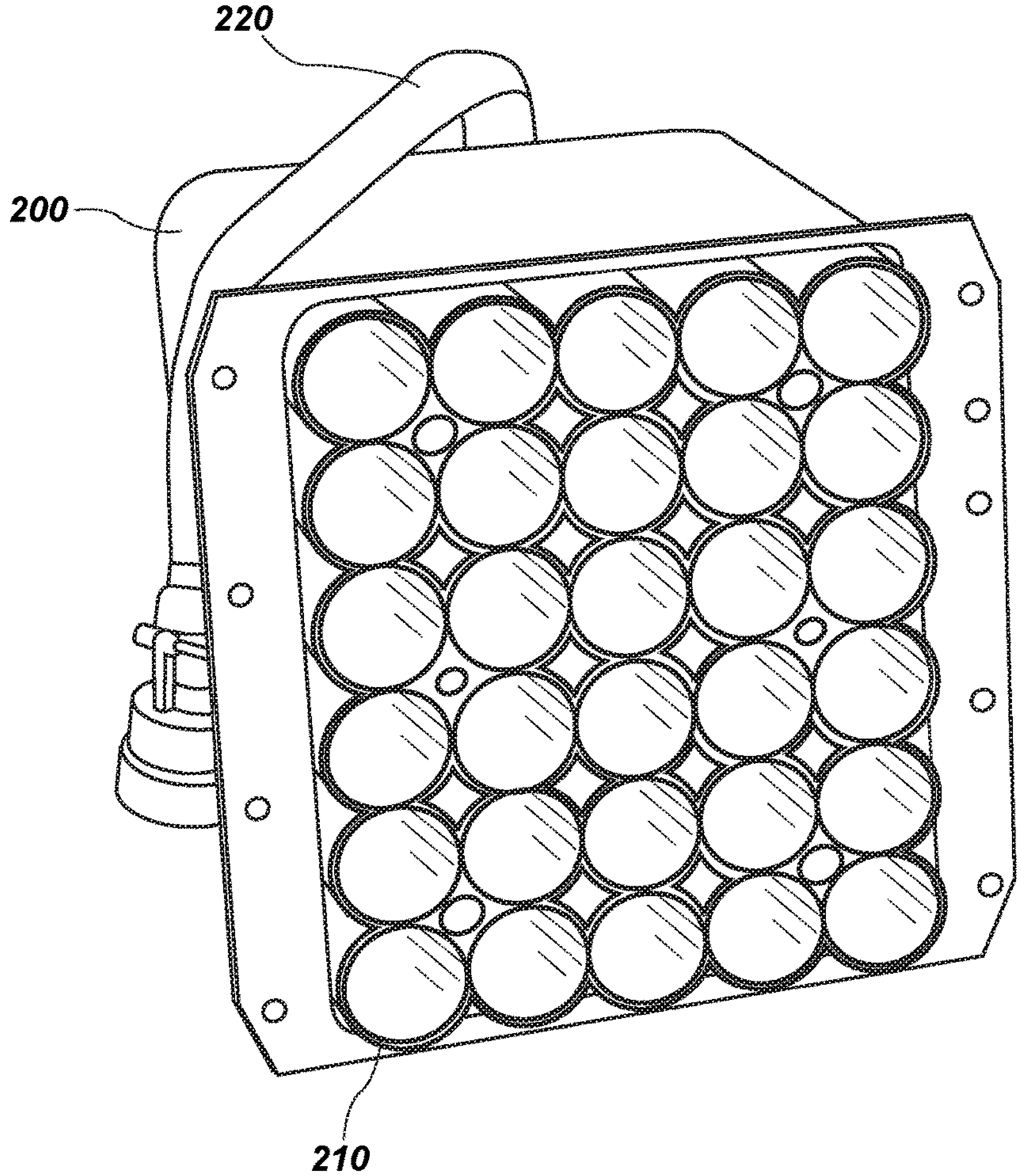



FIG. 2A

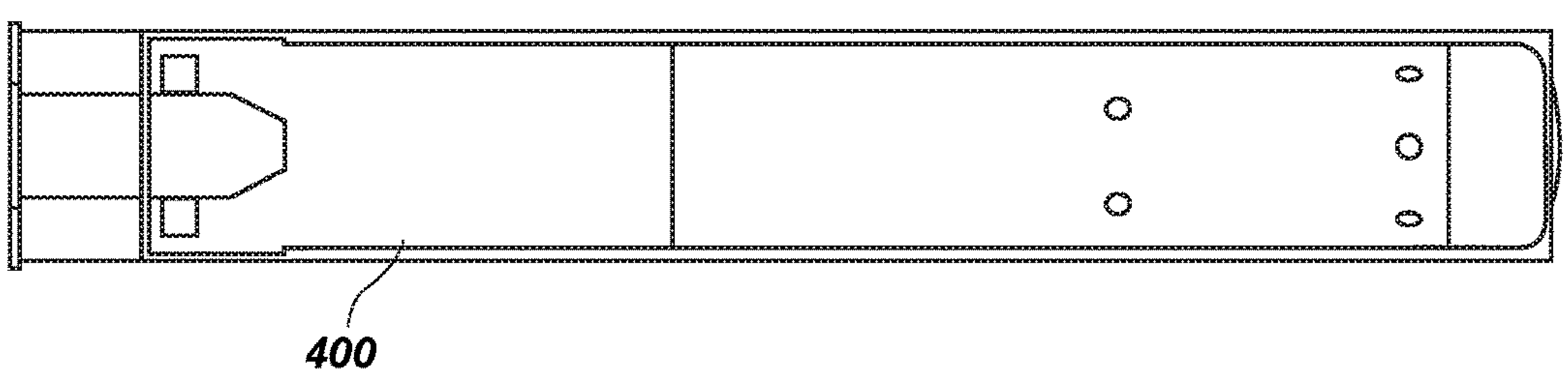
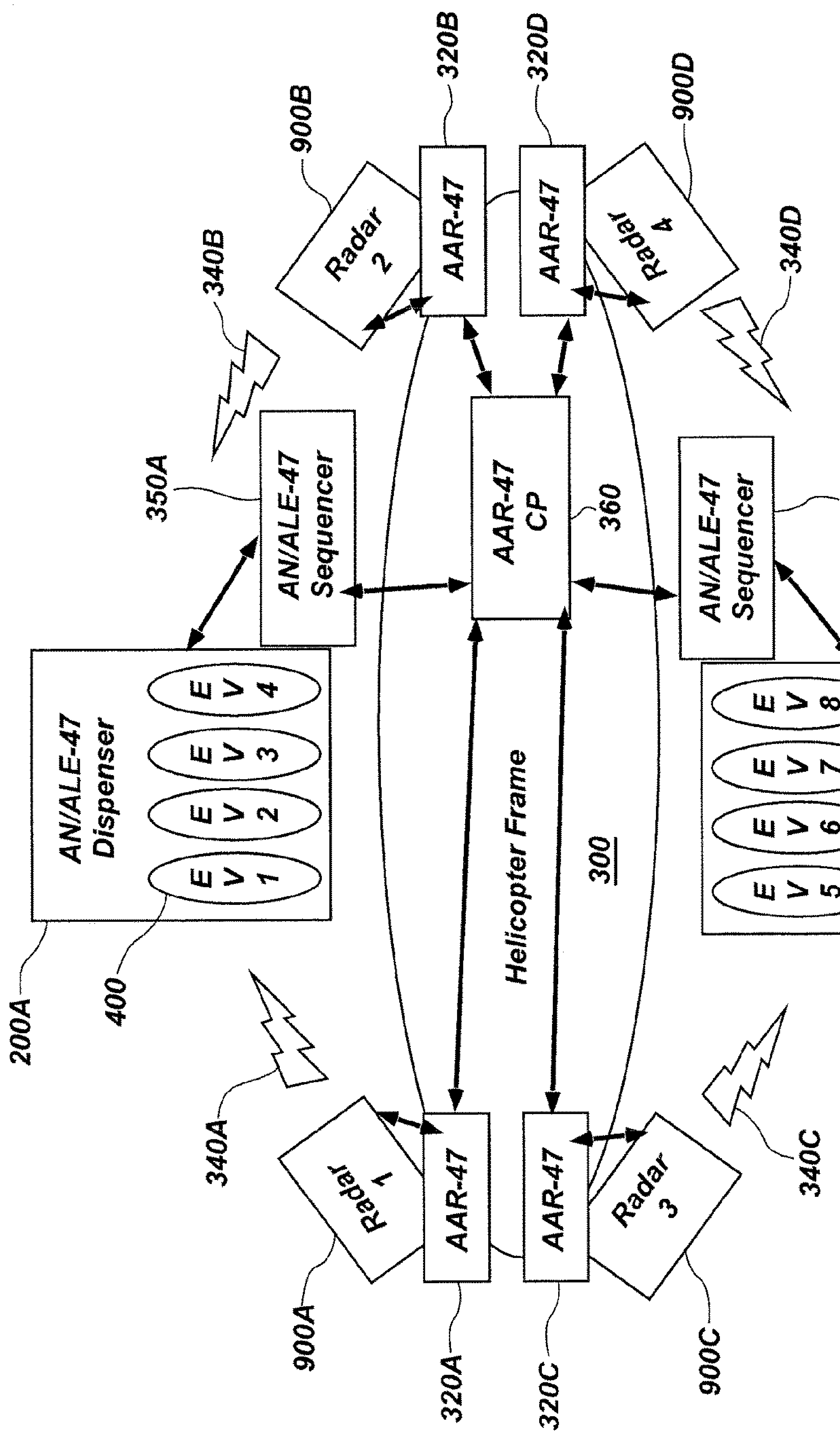



FIG. 2B



900B
320B
320D
900D
Radar 2
AAR-47
AAR-47
Radar 4
340B
340D
350A
AN/ALE-47 Sequencer
AAR-47 CP
360
AN/ALE-47 Sequencer
350B
AN/ALE-47 Dispenser
E V 1
E V 2
E V 3
E V 4
Helicopter Frame
300
E V 5
E V 6
E V 7
E V 8
AN/ALE-47 Dispenser
200A
400
200B
340A
340C
Radar 1
AAR-47
AAR-47
Radar 3
900A
320A
320C
900C


FIG. 3

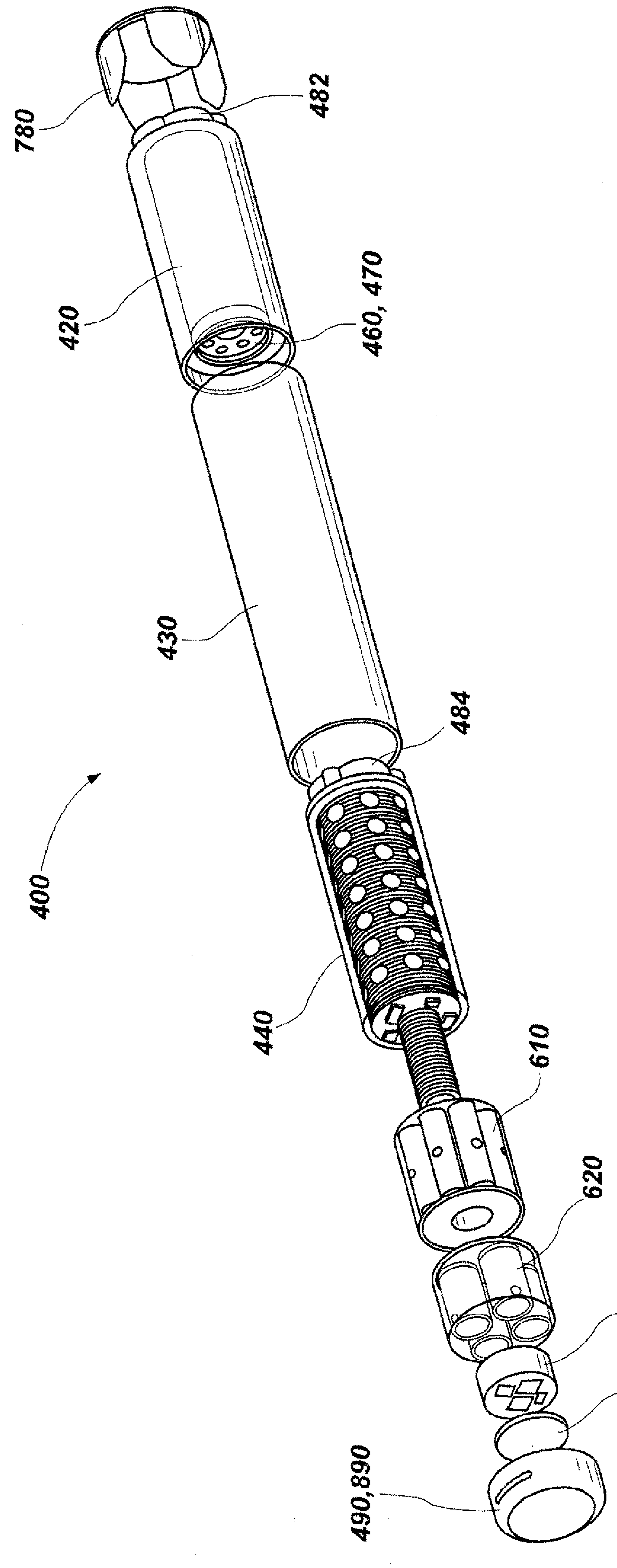



FIG. 4

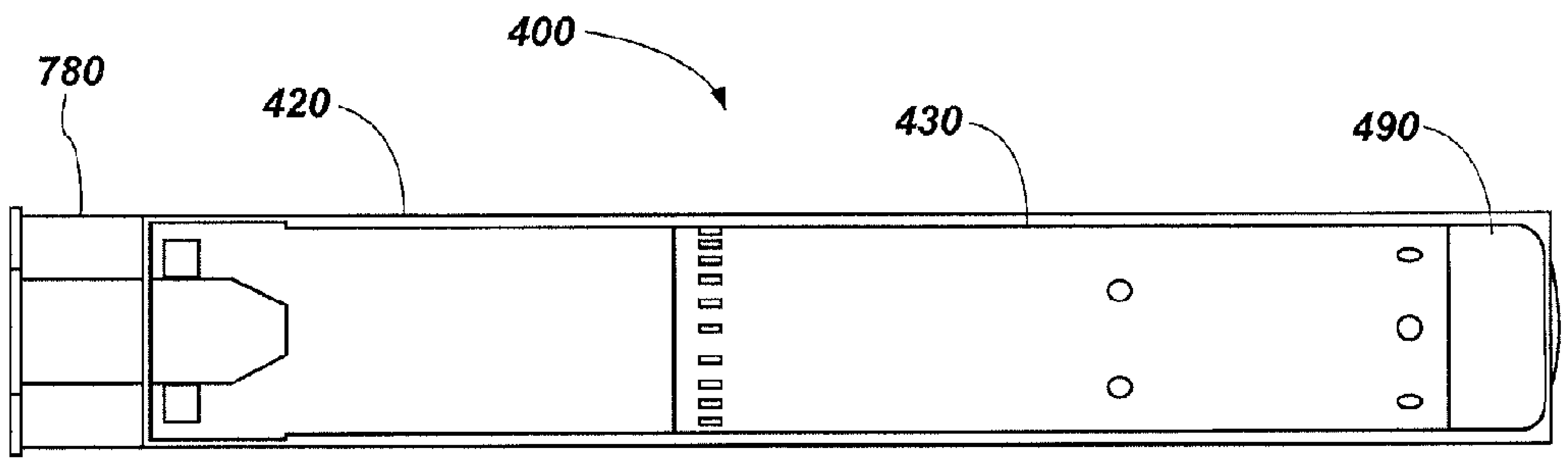



FIG. 5A

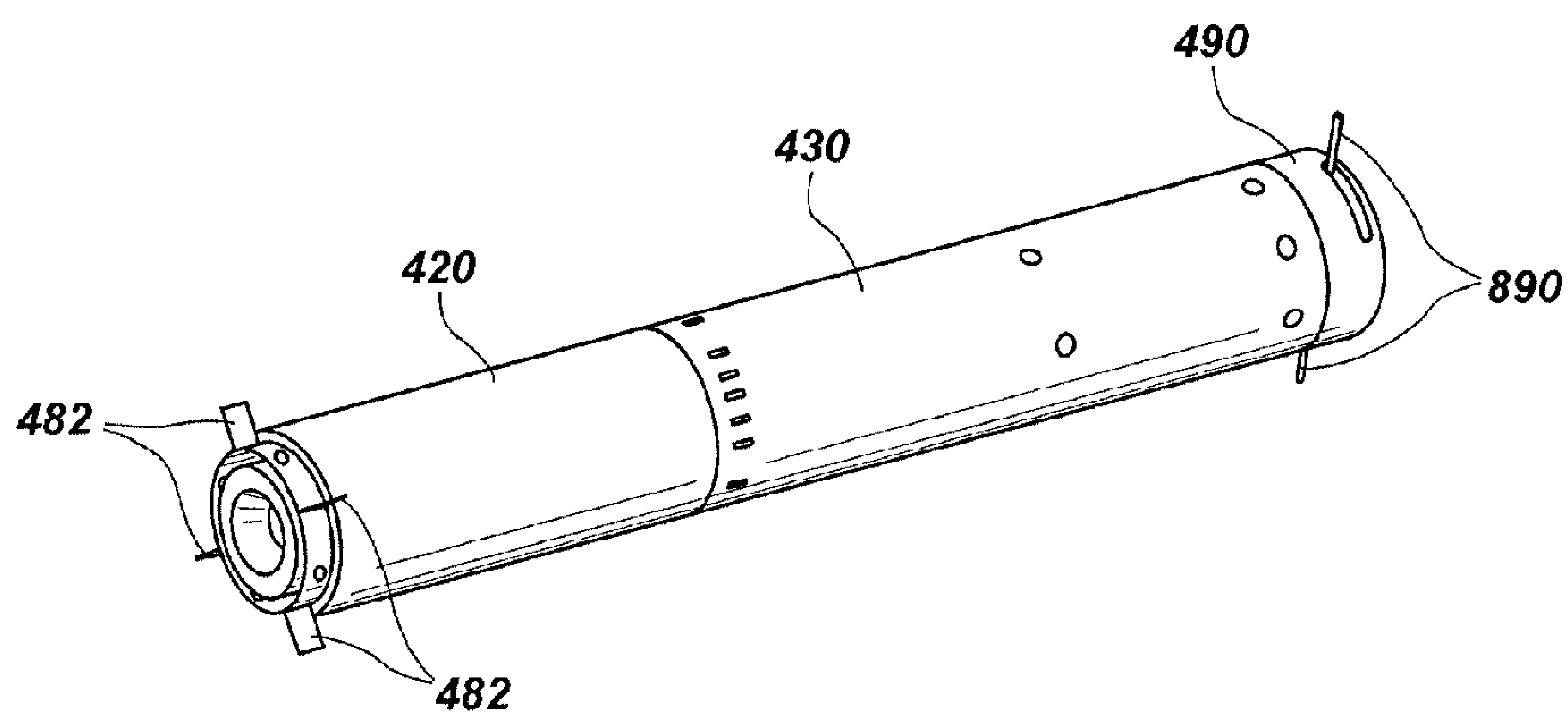



FIG. 5B

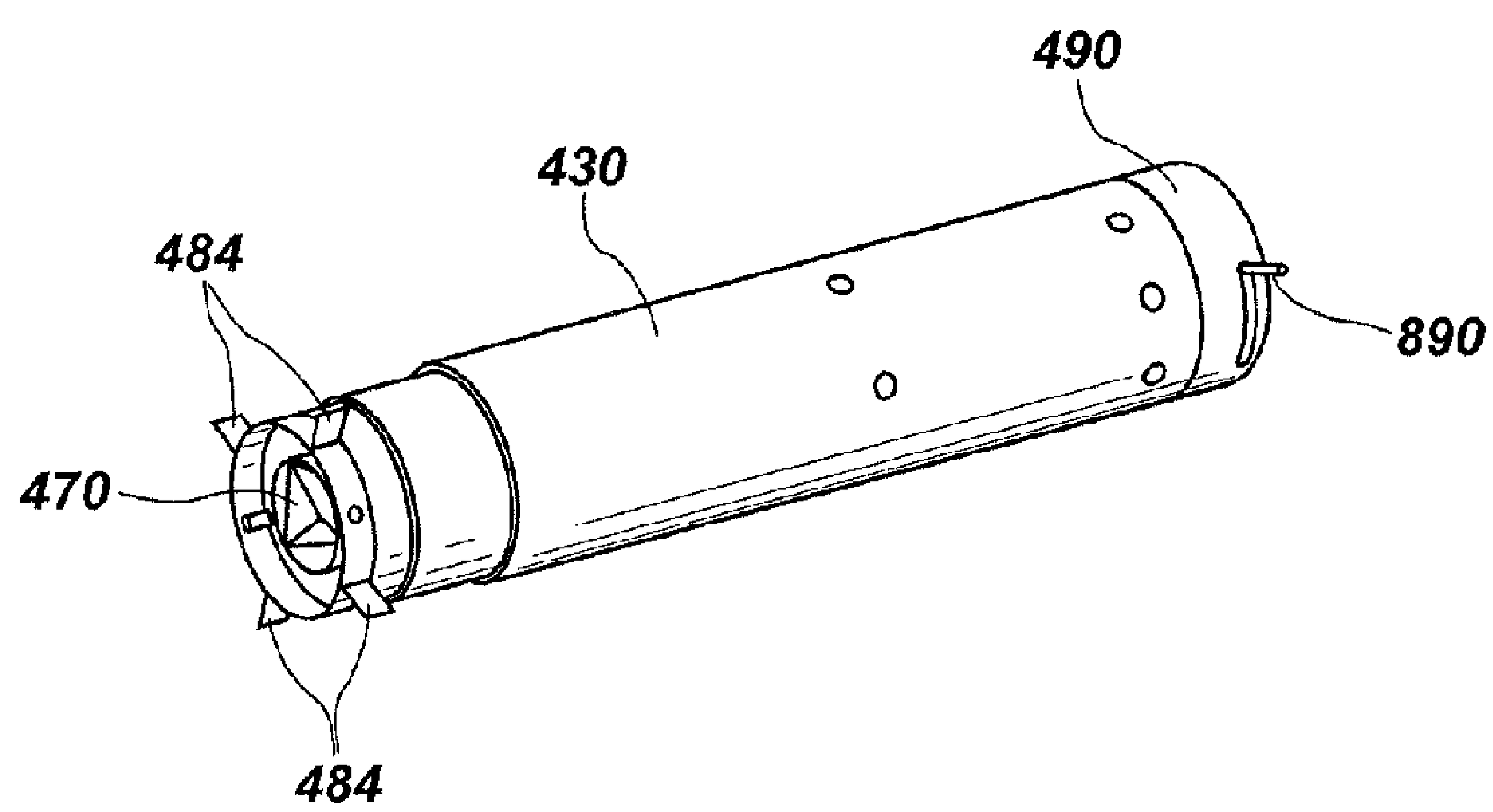



FIG. 5C

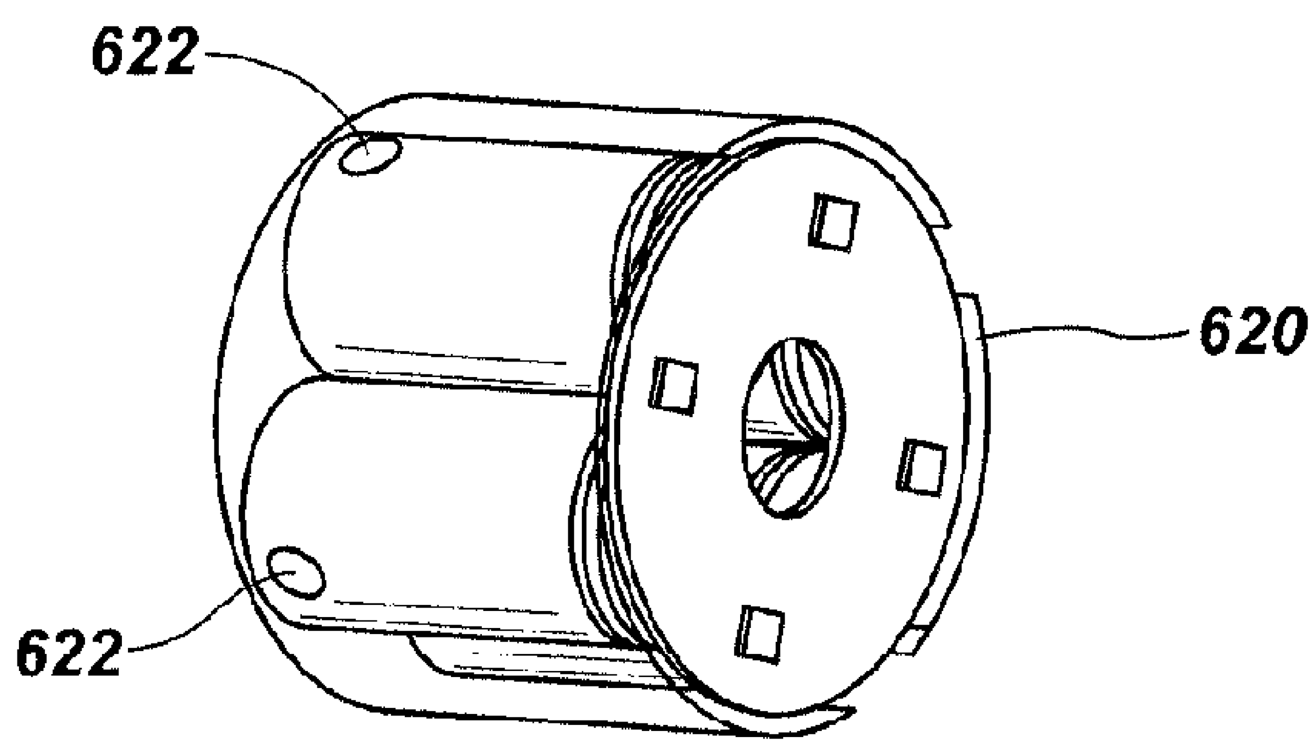



FIG. 6A

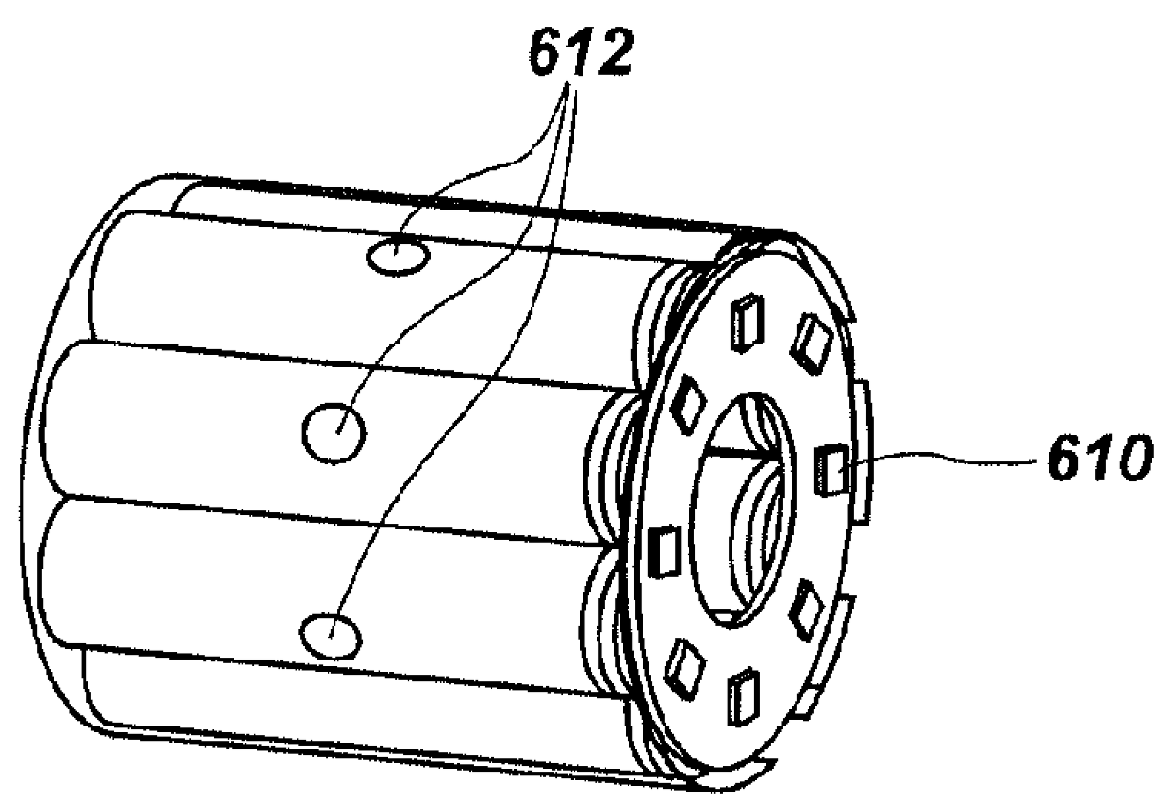



FIG. 6B

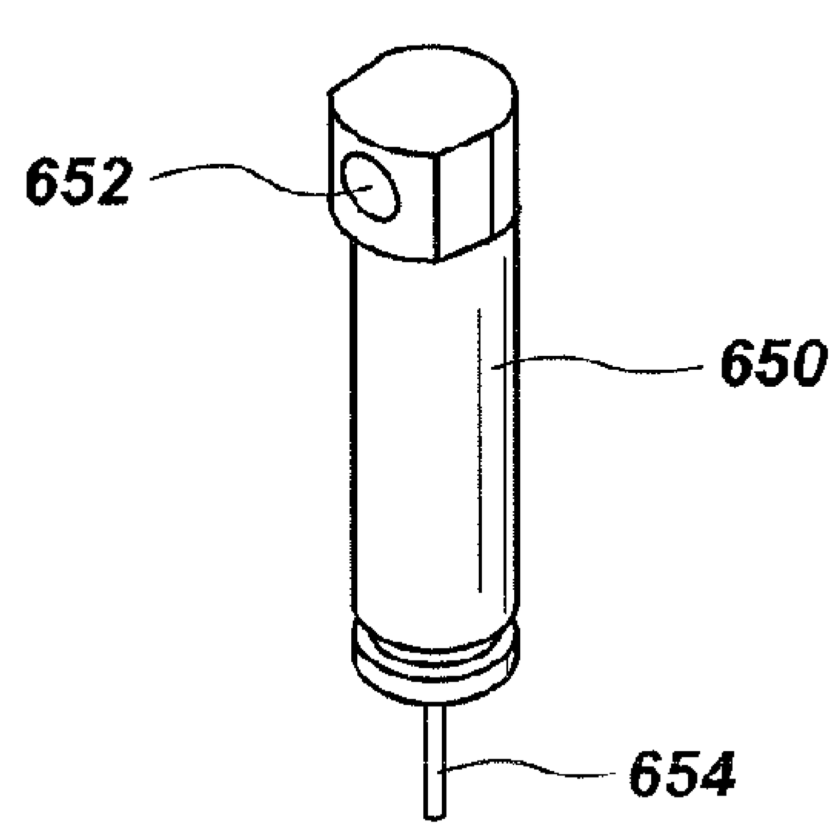



FIG. 6C

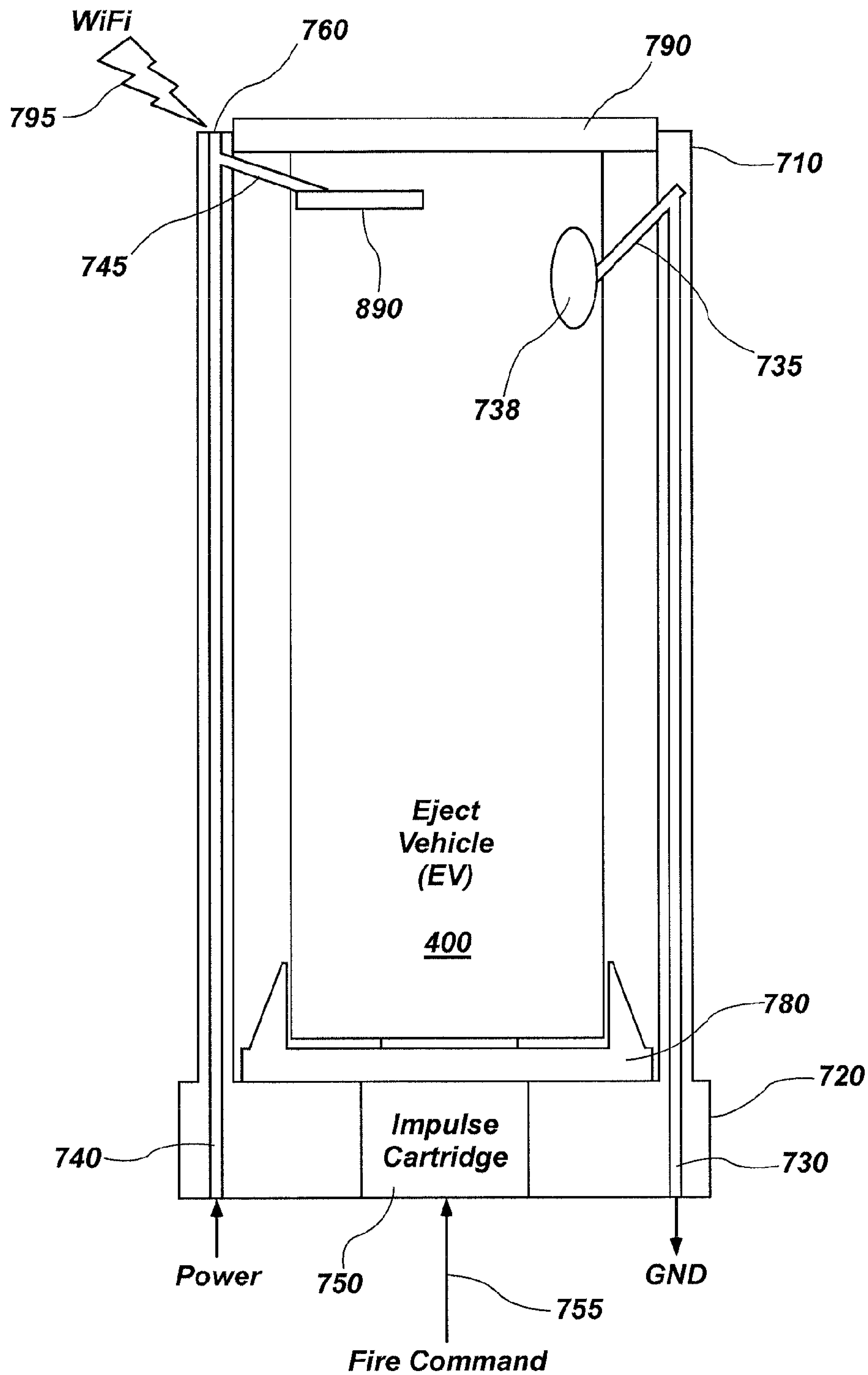

WiFi
760
790
795
710
745
890
735
738
Eject
Vehicle
(EV)
400
780
720
Impulse
Cartridge
740
730
Power
750
GND
755
Fire Command

FIG. 7

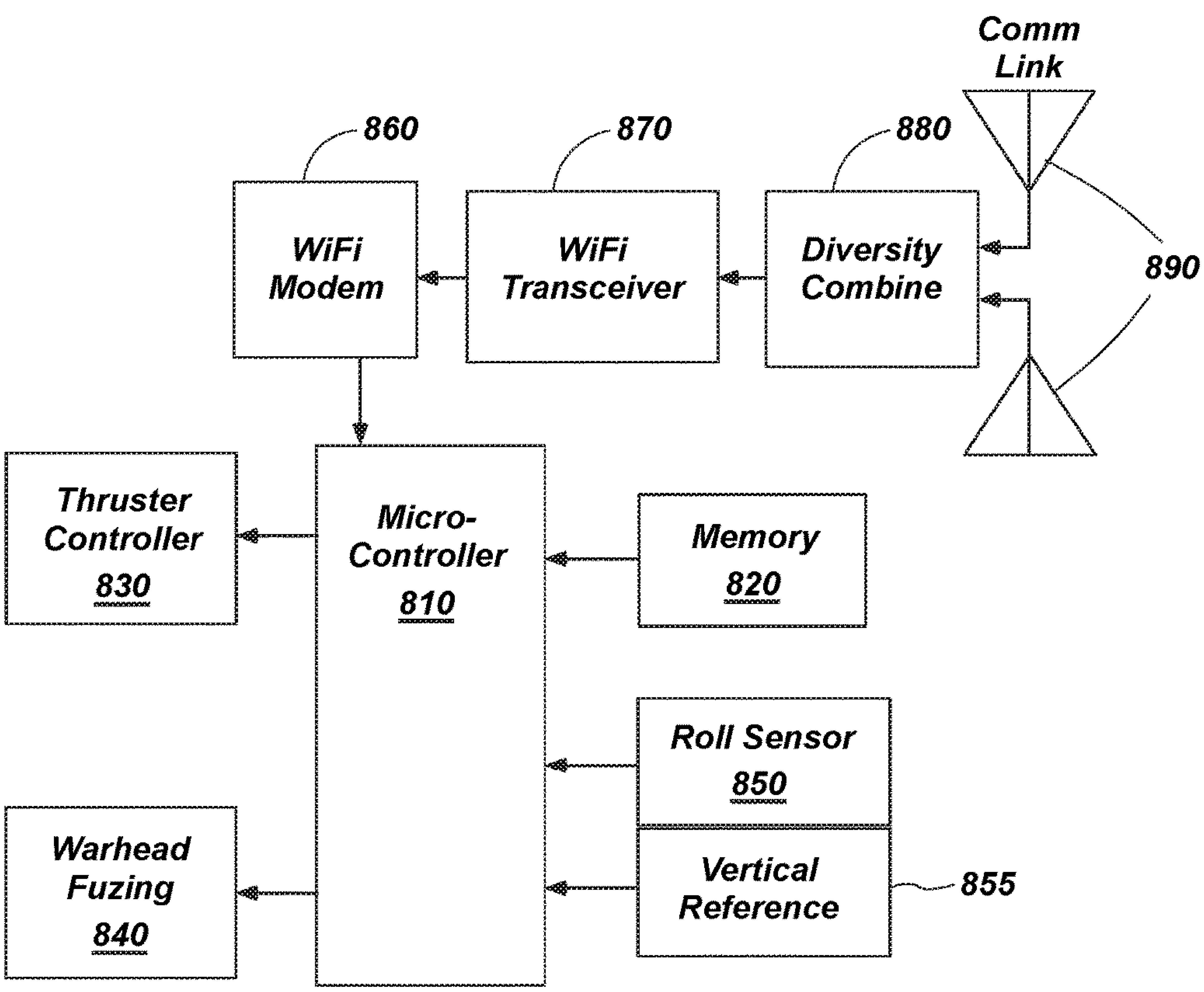

Comm
Link
860
870
880
WiFi
Modem
WiFi
Transceiver
Diversity
Combine
890
Thruster
Controller
830
Micro-
Controller
810
Memory
820
Roll Sensor
850
Warhead
Fuzing
840
Vertical
Reference
855

FIG. 8

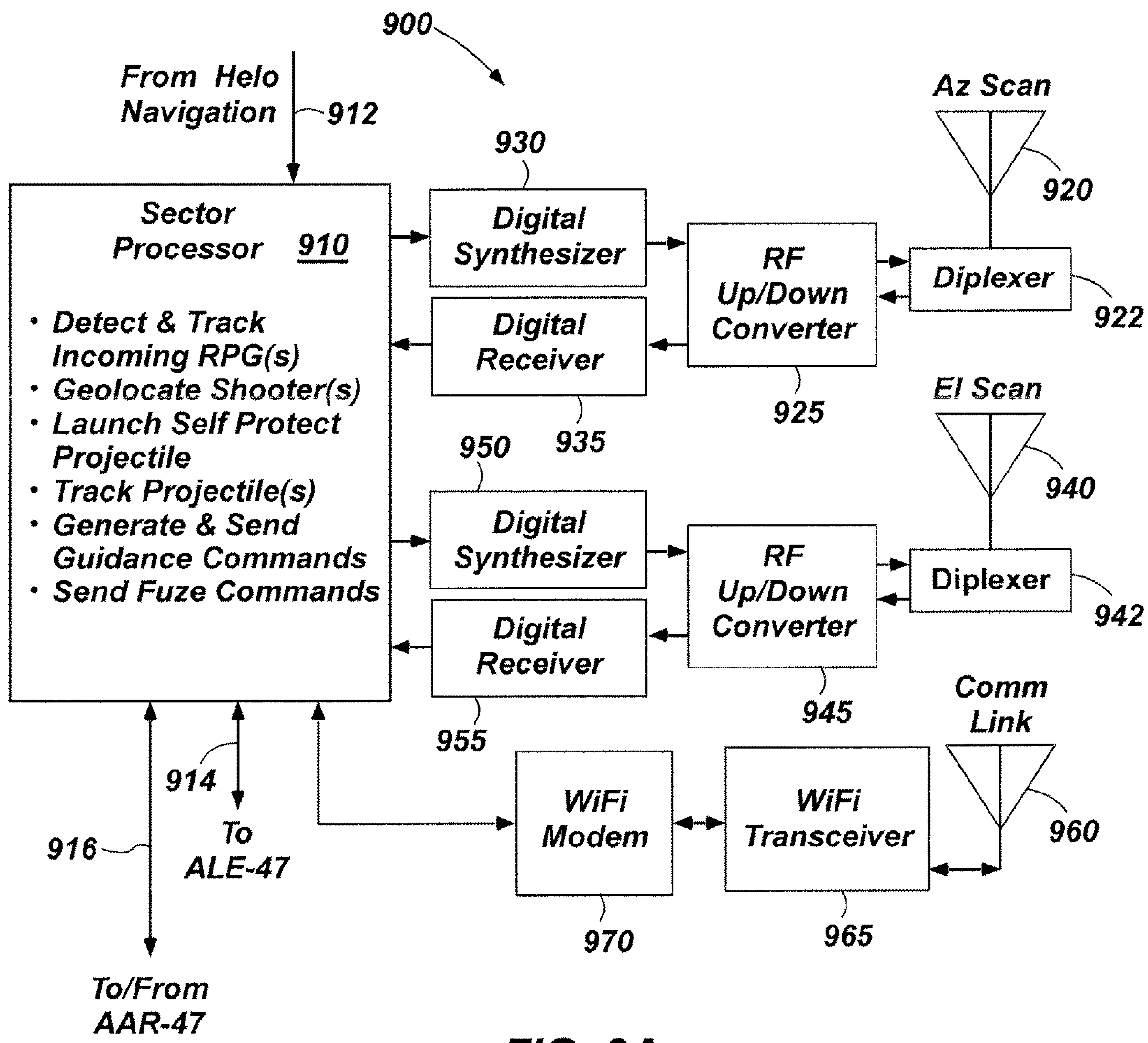

900
From Helo Navigation
912
930
Az Scan
920
Sector Processor 910
• Detect & Track Incoming RPG(s)
• Geolocate Shooter(s)
• Launch Self Protect Projectile
• Track Projectile(s)
• Generate & Send Guidance Commands
• Send Fuze Commands
Digital Synthesizer
Digital Receiver
RF Up/Down Converter
Diplexer
922
925
935
El Scan
950
940
Digital Synthesizer
Digital Receiver
RF Up/Down Converter
Diplexer
942
945
955
Comm Link
914
To ALE-47
916
WiFi Modem
WiFi Transceiver
960
970
965
To/From AAR-47

FIG. 9A

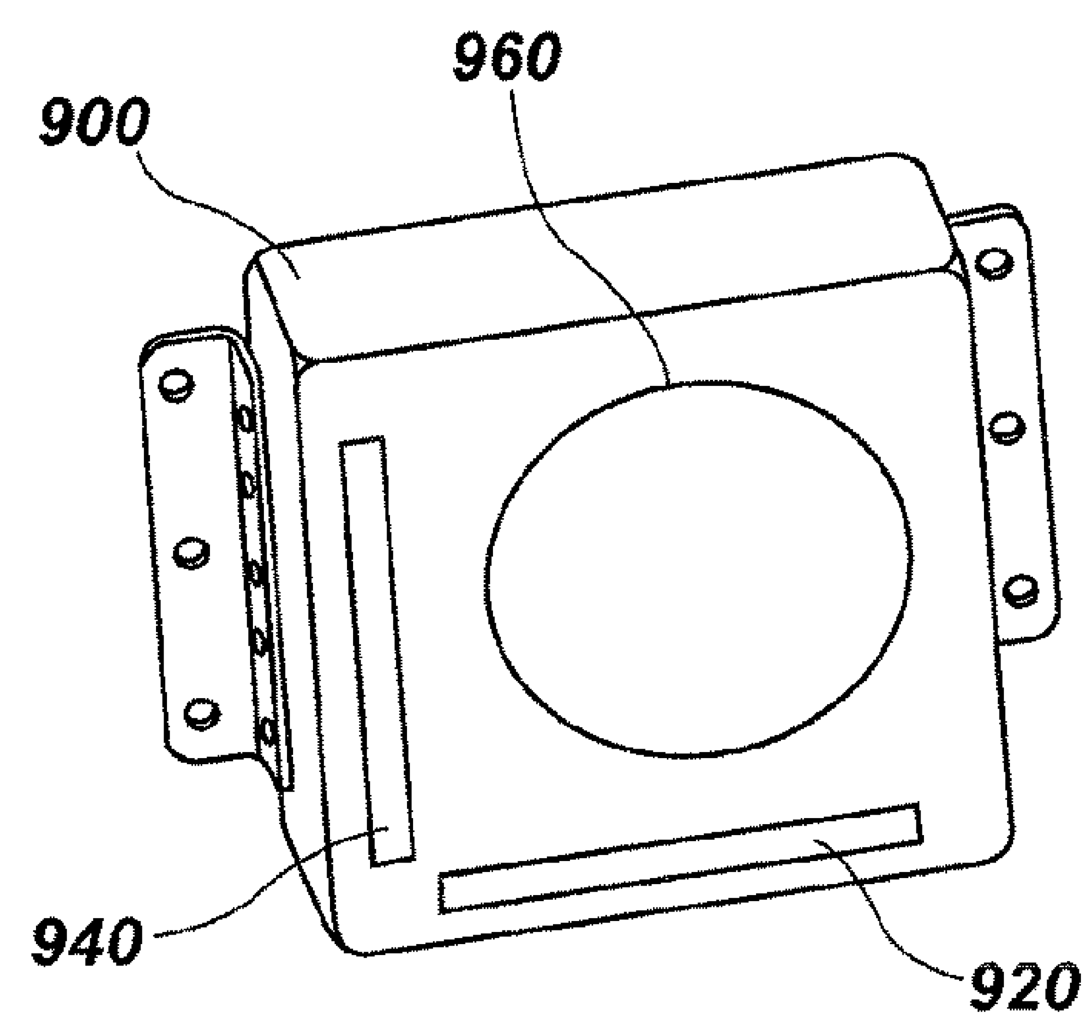

900
960
940
920

FIG. 9B

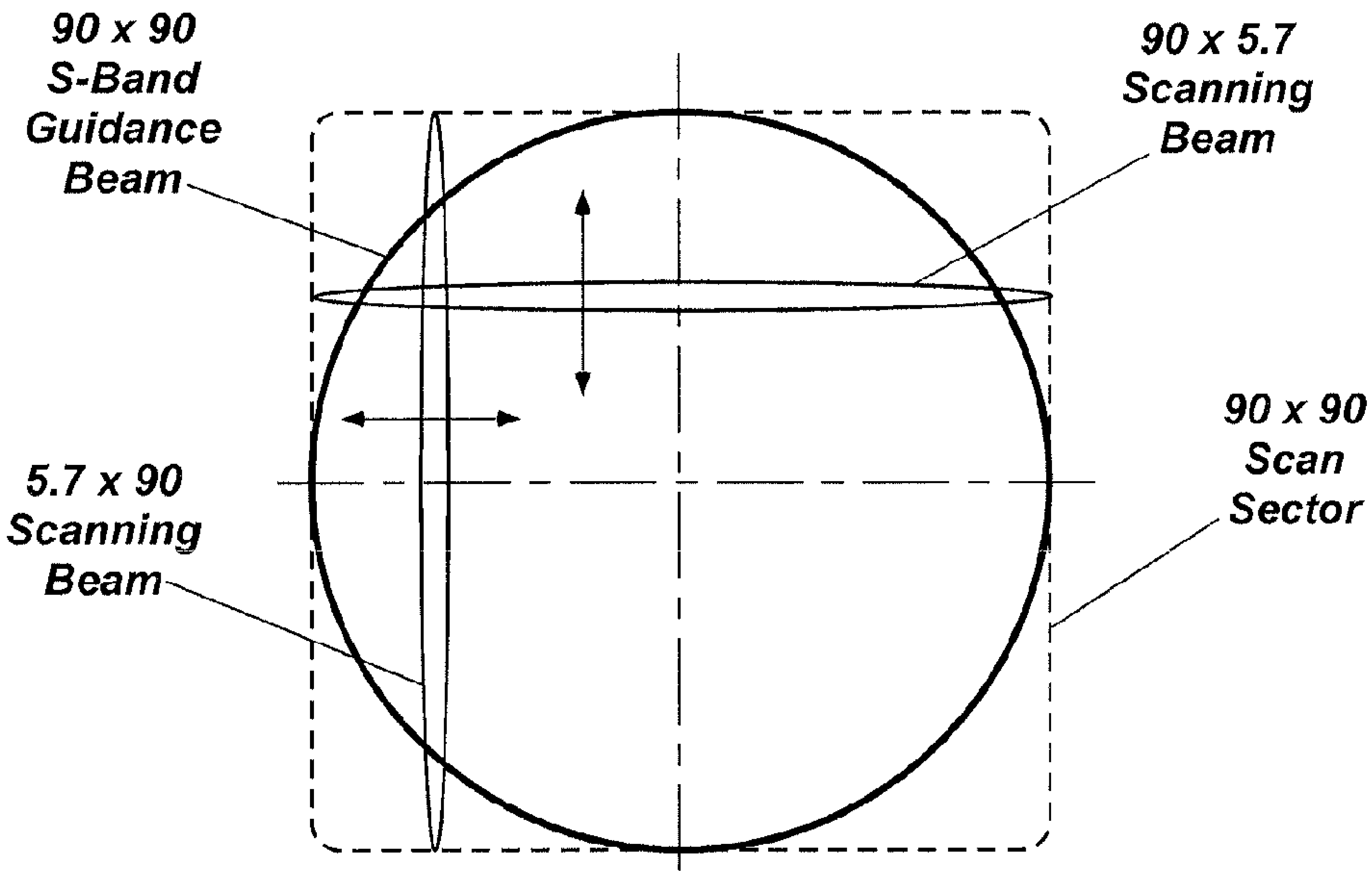



FIG. 10A

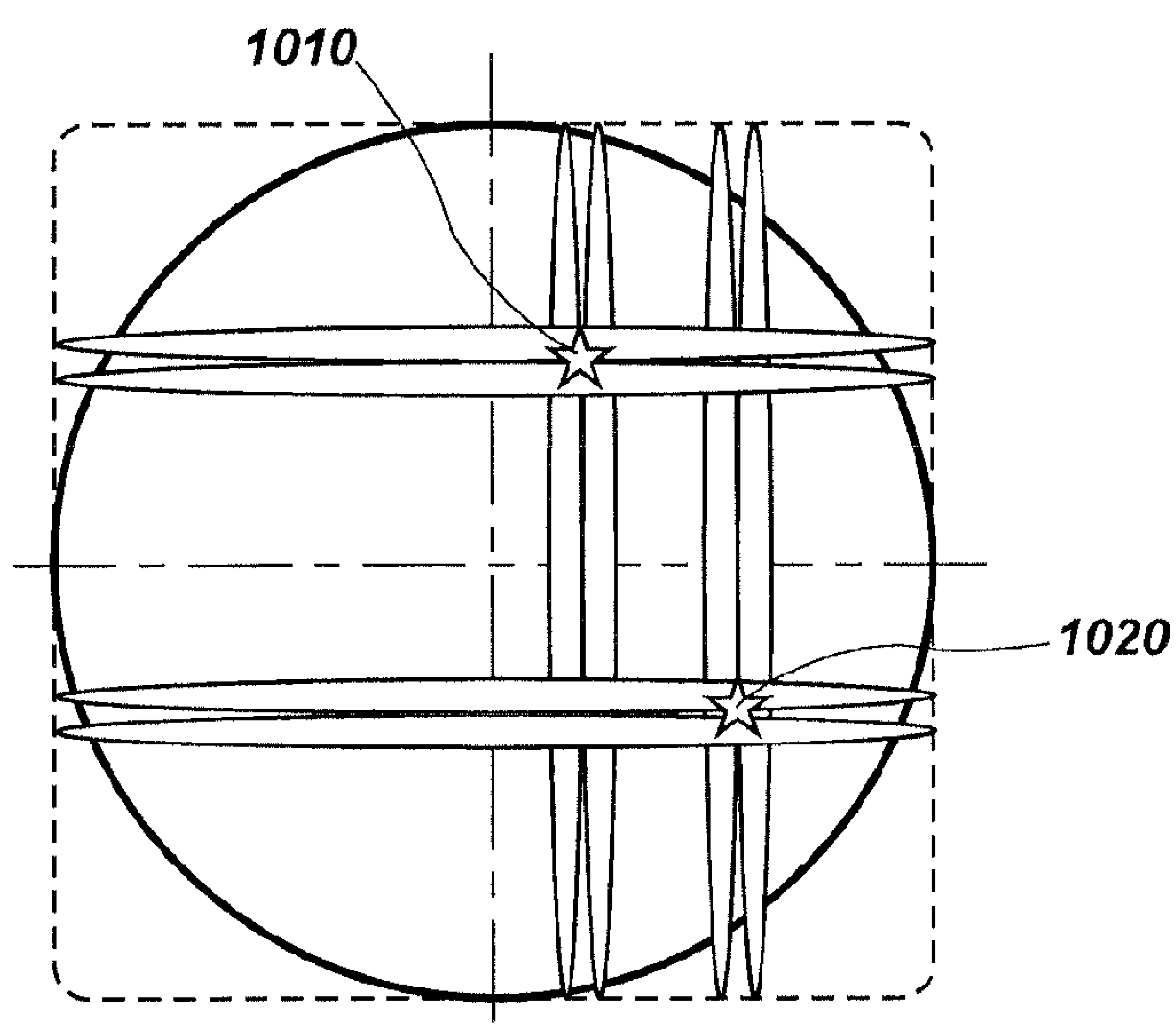



FIG. 10B

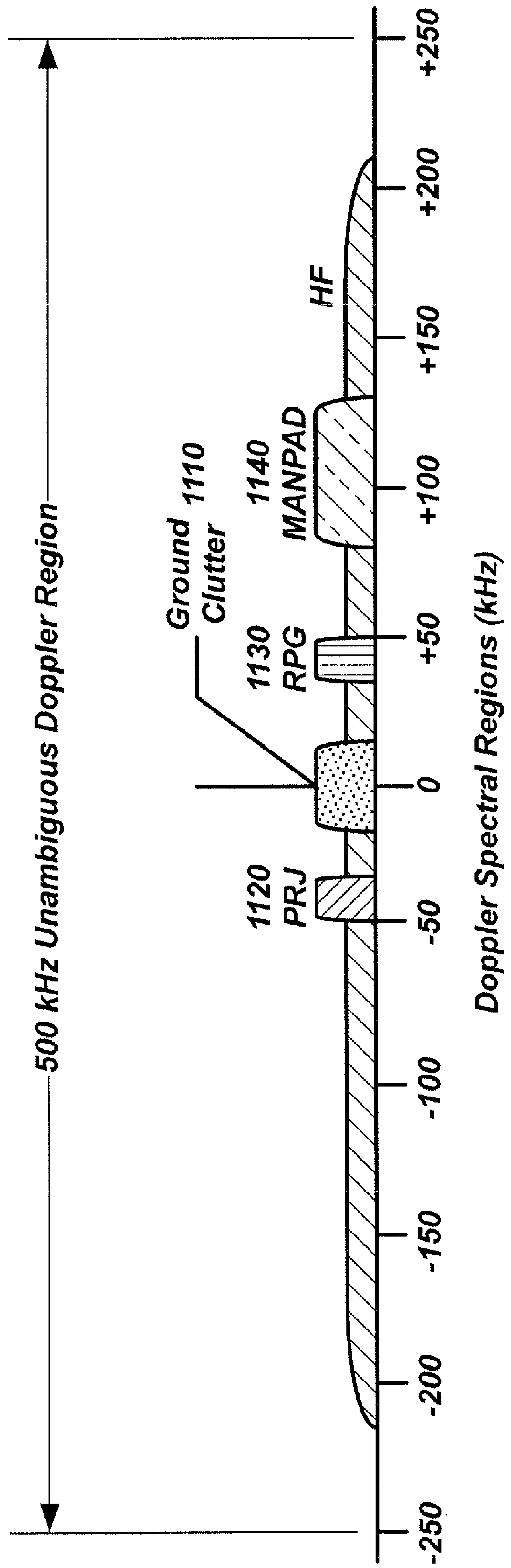

500 kHz Unambiguous Doppler Region
Ground Clutter
1110
1120
PRJ
1130
RPG
1140
MANPAD
HF
+250
+200
+150
+100
+50
0
-50
-100
-150
-200
-250
Doppler Spectral Regions (kHz)

FIG. 11

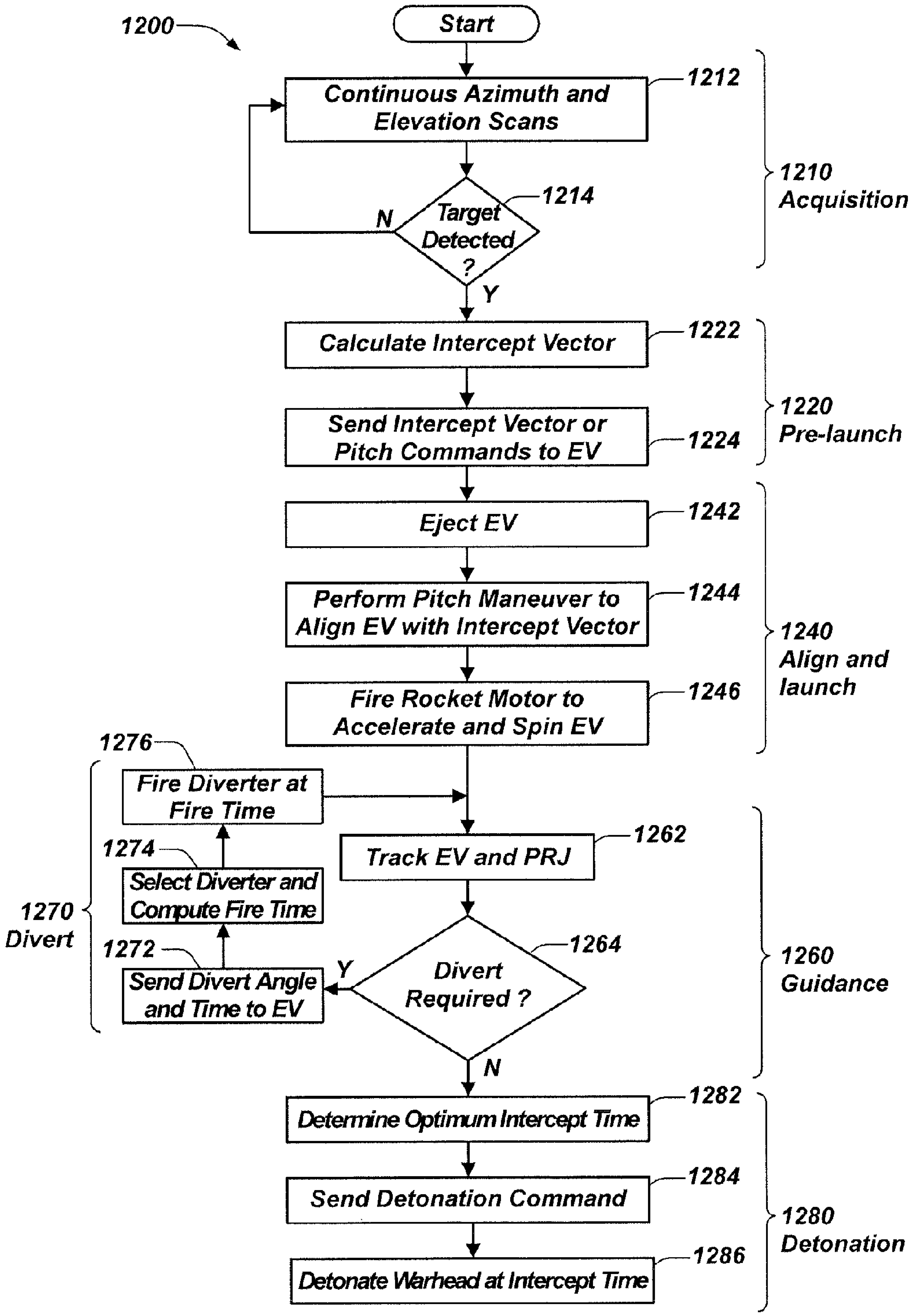

1200
Start
Continuous Azimuth and Elevation Scans
1212
Target Detected ?
1214
N
Y
1210 Acquisition
Calculate Intercept Vector
1222
Send Intercept Vector or Pitch Commands to EV
1224
1220 Pre-launch
Eject EV
1242
Perform Pitch Maneuver to Align EV with Intercept Vector
1244
Fire Rocket Motor to Accelerate and Spin EV
1246
1240 Align and launch
1276
Fire Diverter at Fire Time
1274
Select Diverter and Compute Fire Time
1272
Send Divert Angle and Time to EV
1270 Divert
Track EV and PRJ
1262
Divert Required ?
1264
Y
N
1260 Guidance
Determine Optimum Intercept Time
1282
Send Detonation Command
1284
Detonate Warhead at Intercept Time
1286
1280 Detonation

FIG. 12

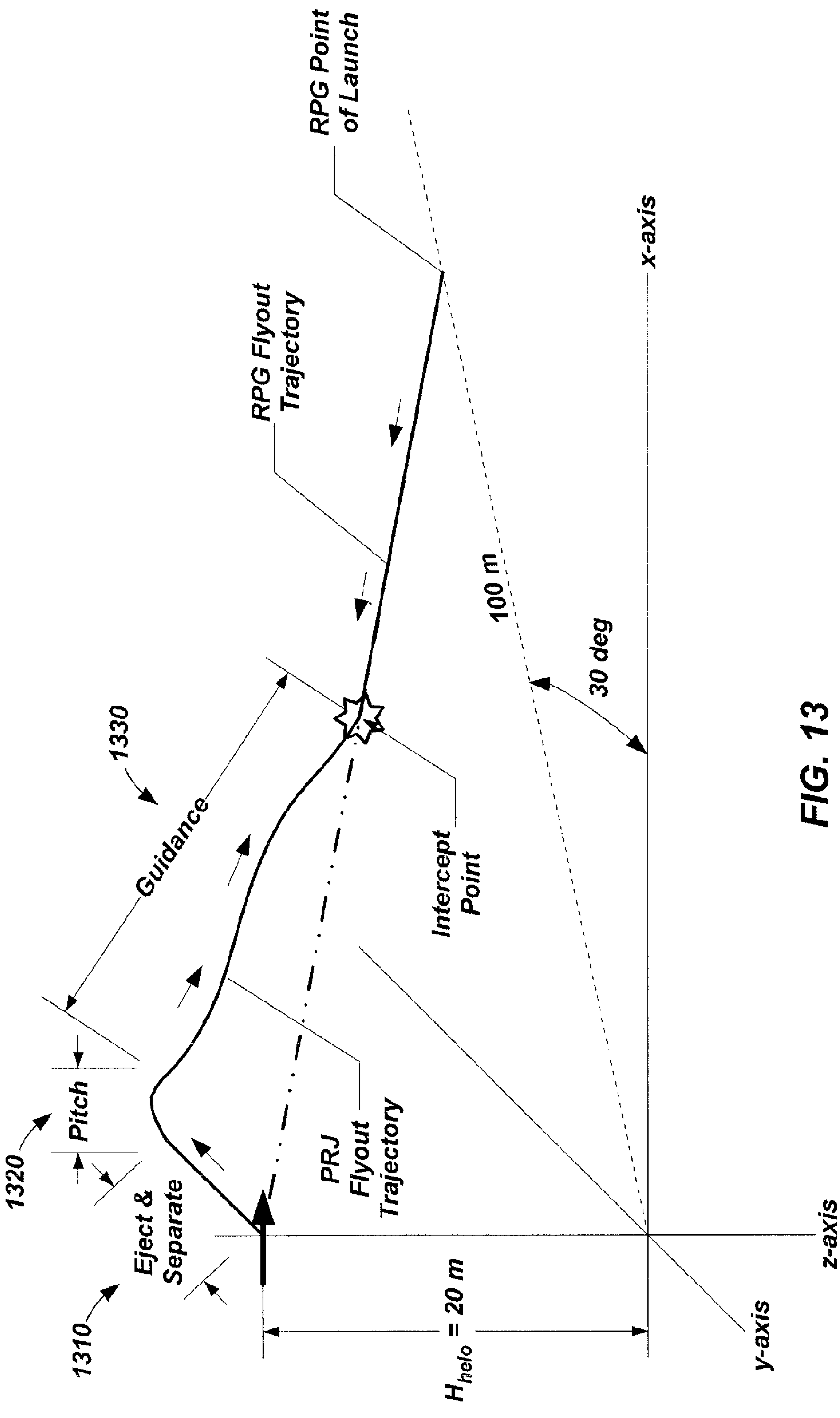

RPG Point of Launch
x-axis
RPG Flyout Trajectory
100 m
30 deg
1330
Guidance
Intercept Point
1320
Pitch
PRJ Flyout Trajectory
1310
Eject & Separate
$H_{helo}$ = 20 m
z-axis
y-axis

FIG. 13

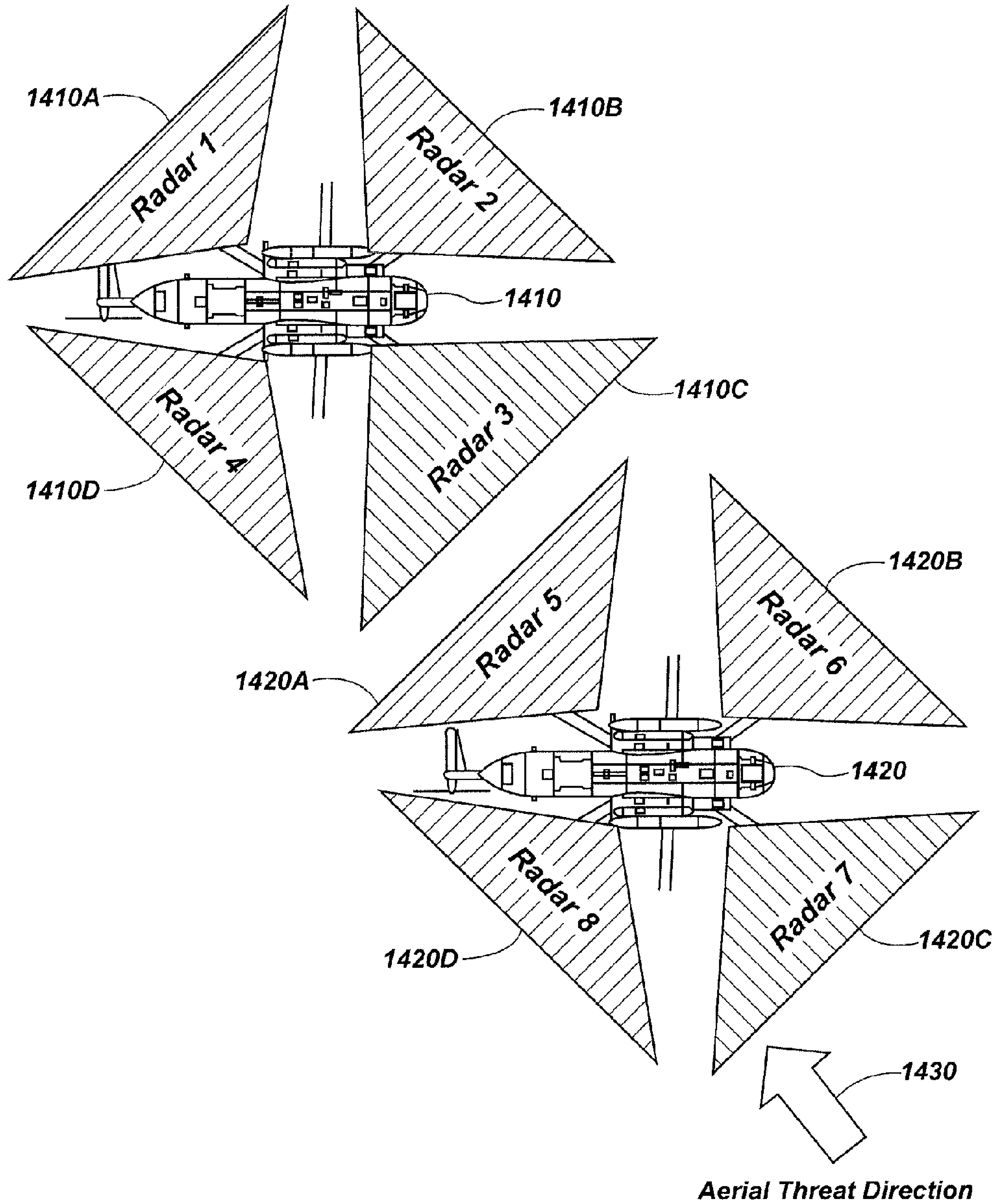

1410A
Radar 1
1410B
Radar 2
1410
1410C
Radar 3
Radar 4
1410D
1420B
Radar 5
Radar 6
1420A
1420
Radar 8
Radar 7
1420D
1420C
1430
Aerial Threat Direction

FIG. 14

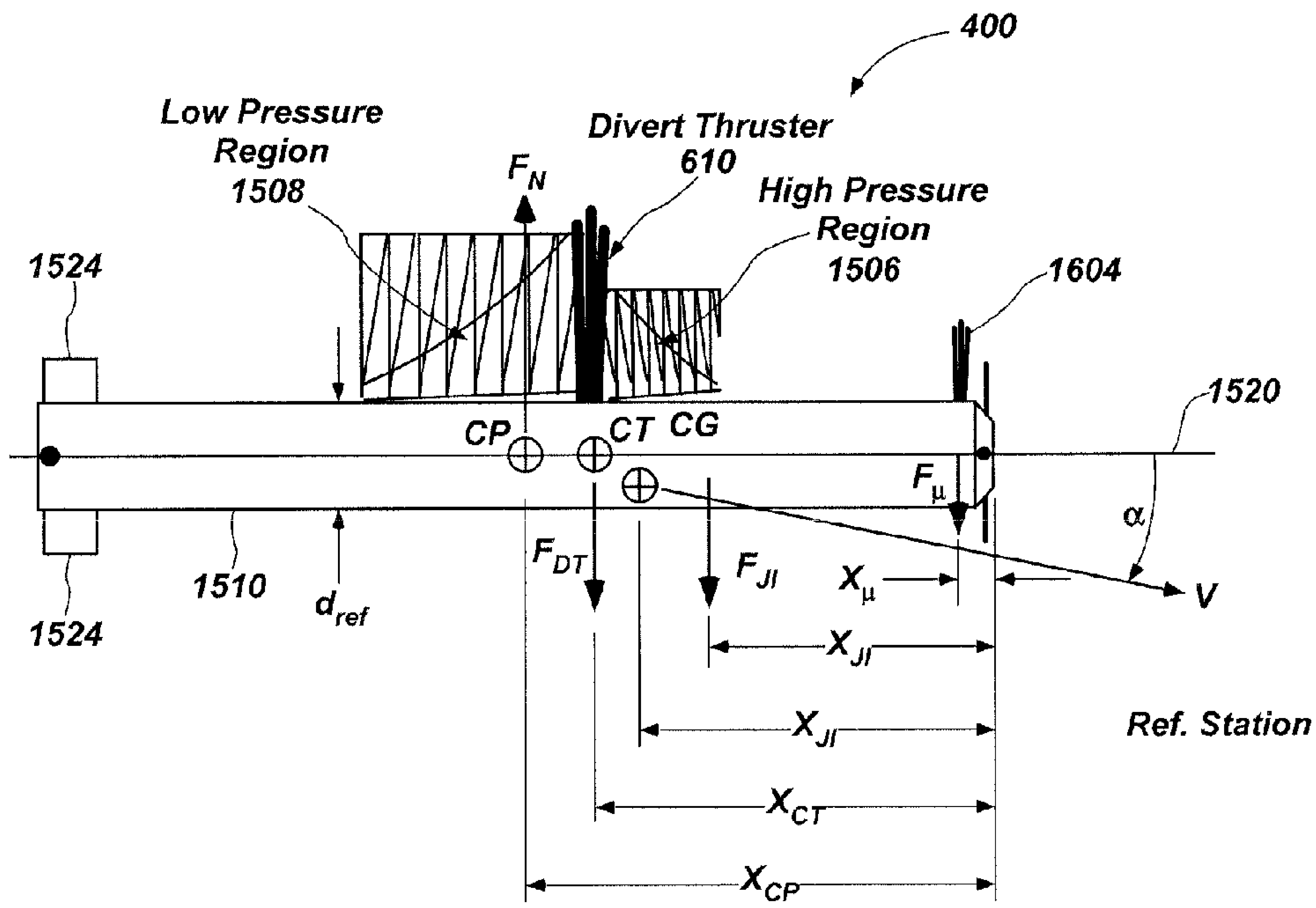



FIG. 15

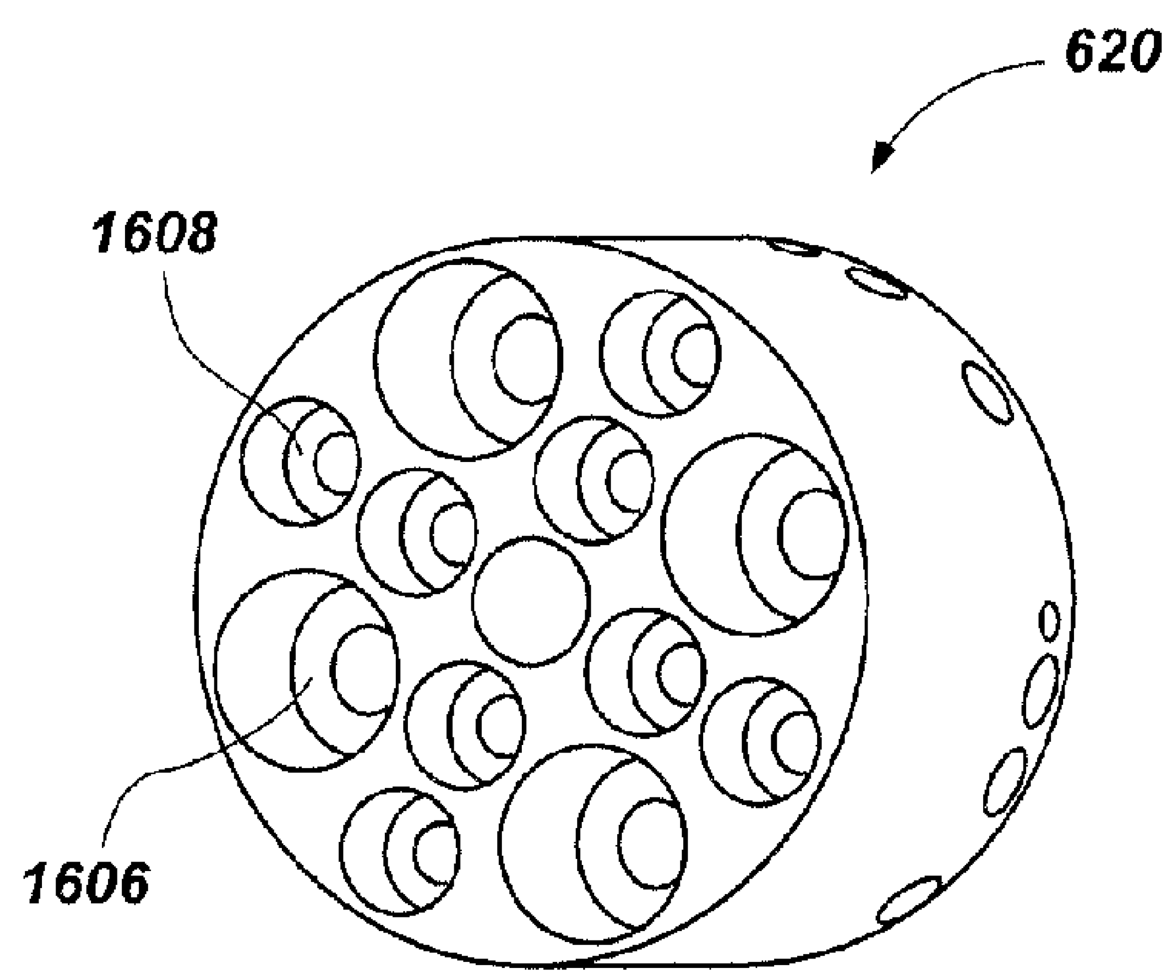



FIG. 16A

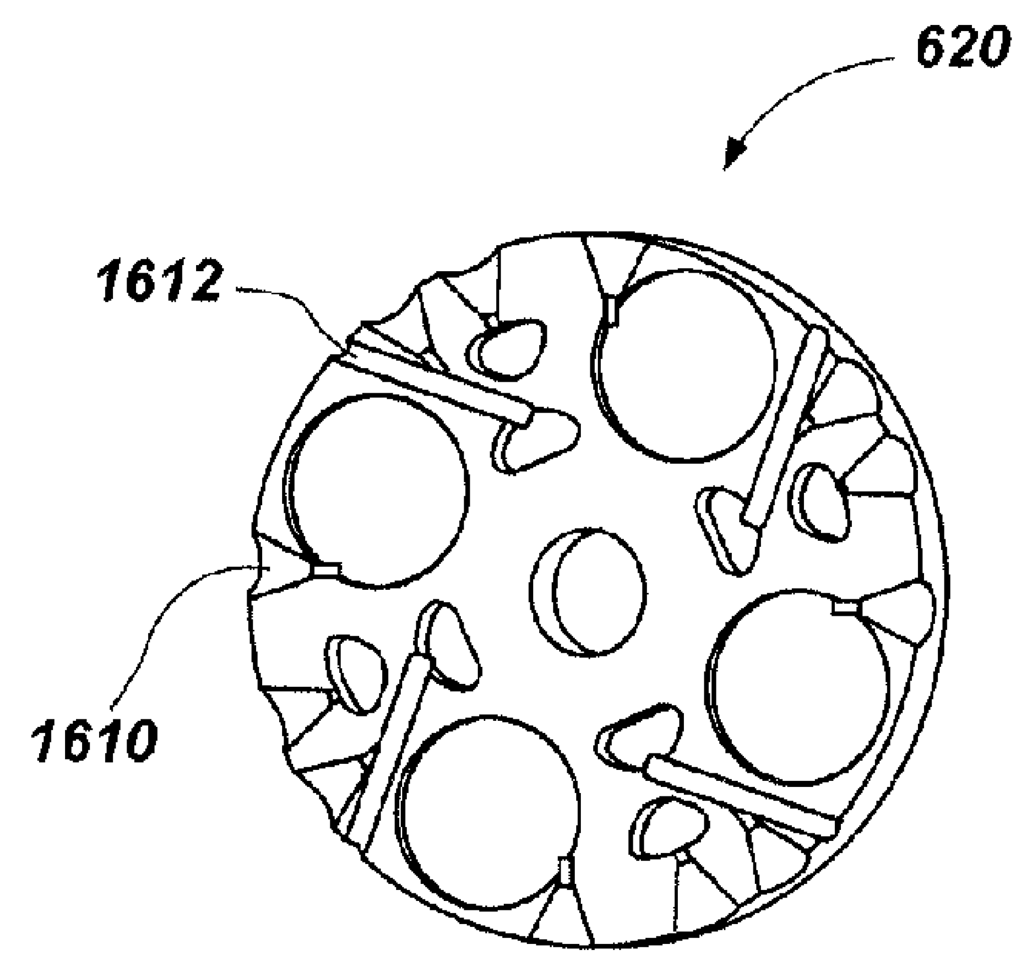
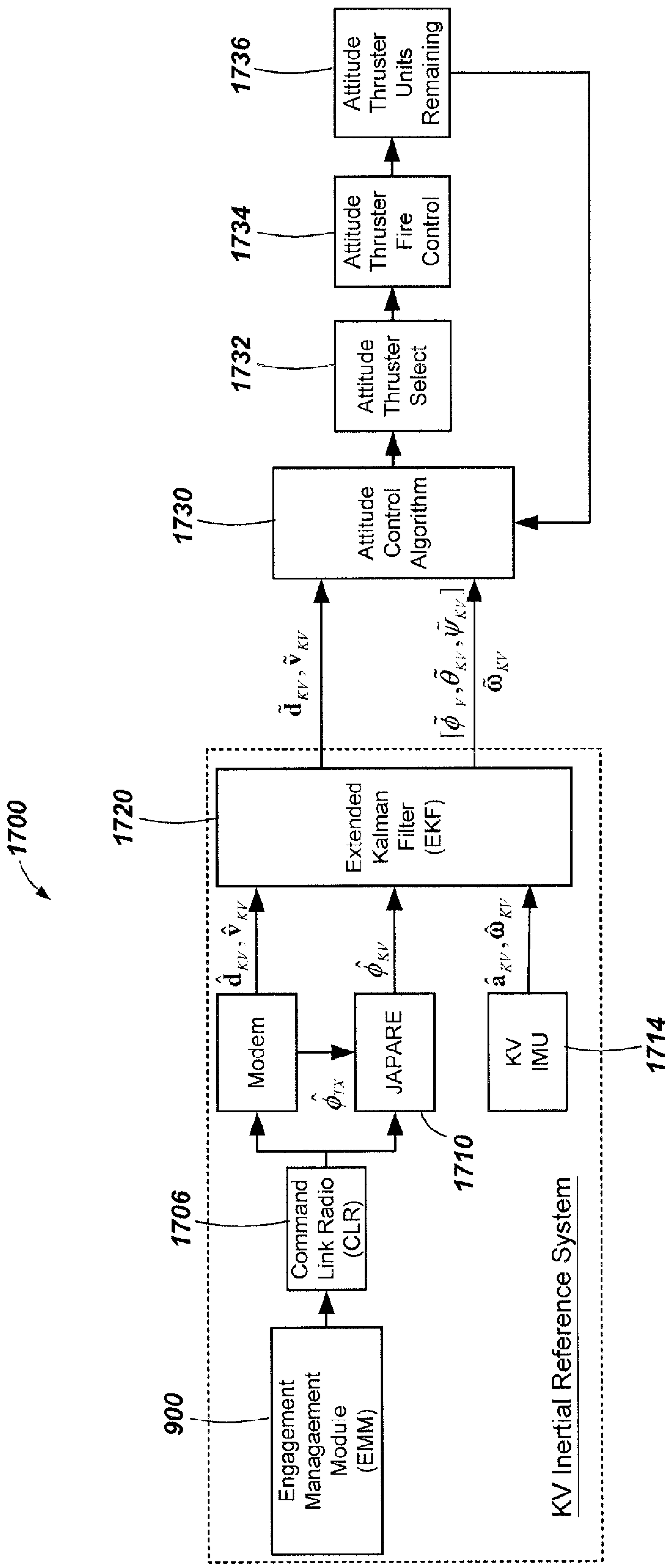



FIG. 16B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Engagement Managaement Module (EMM)
900
Command Link Radio (CLR)
1706
Modem
JAPARE
1710
KV IMU
1714
Extended Kalman Filter (EKF)
1720
KV Inertial Reference System
Attitude Control Algorithm
1730
Attitude Thruster Select
1732
Attitude Thruster Fire Control
1734
Attitude Thruster Units Remaining
1736

FIG. 17

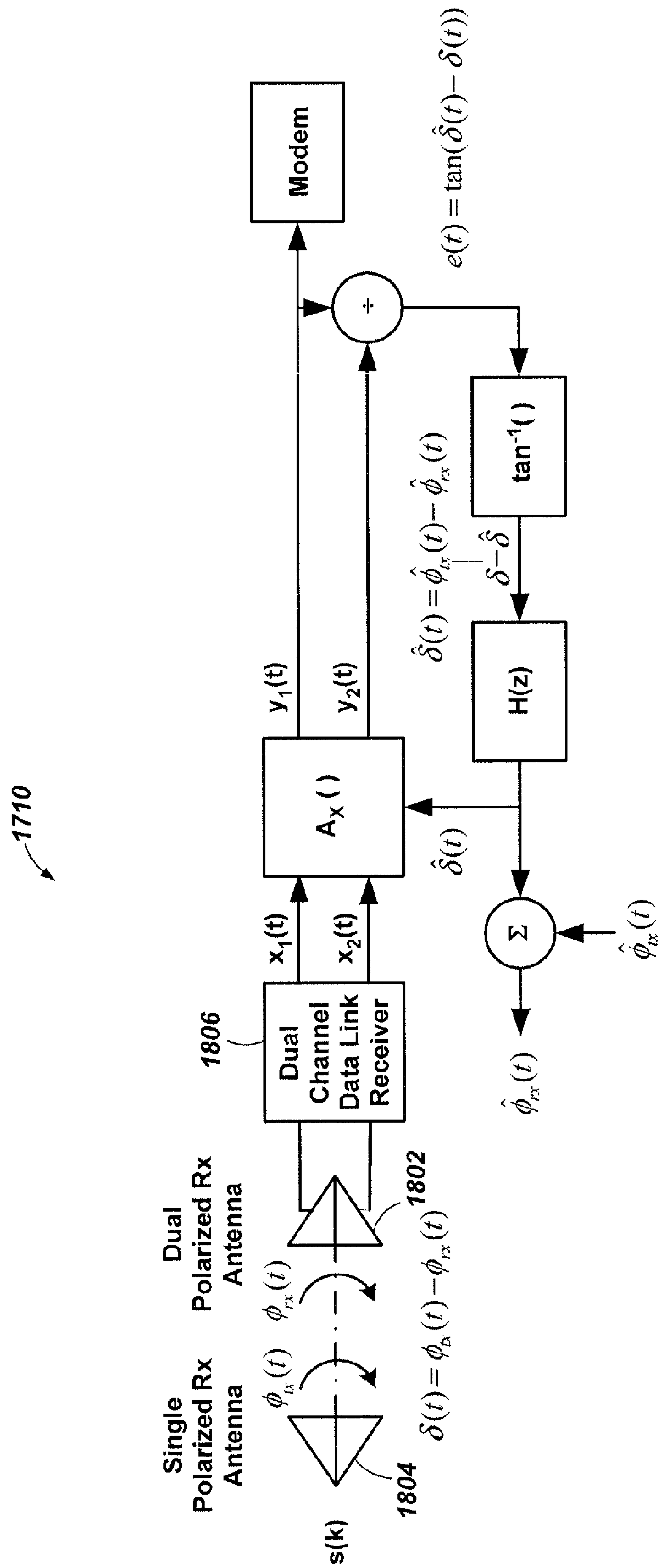

1710
Modem
$e(t) = \tan(\hat{\delta}(t) - \delta(t))$
$\div$
$\tan^{-1}()$
$\hat{\delta}(t) = \hat{\phi}_{tx}(t) - \hat{\phi}_{rx}(t)$
$\delta - \hat{\delta}$
H(z)
$y_1(t)$
$y_2(t)$
$A_X()$
$\hat{\delta}(t)$
$x_1(t)$
$x_2(t)$
$\Sigma$
$\hat{\phi}_{tx}(t)$
$\hat{\phi}_{rx}(t)$
1806
Dual Channel Data Link Receiver
Dual Polarized Rx Antenna
1802
$\phi_{rx}(t)$
$\phi_{tx}(t)$
$\delta(t) = \phi_{tx}(t) - \phi_{rx}(t)$
Single Polarized Rx Antenna
1804
s(k)

FIG. 18

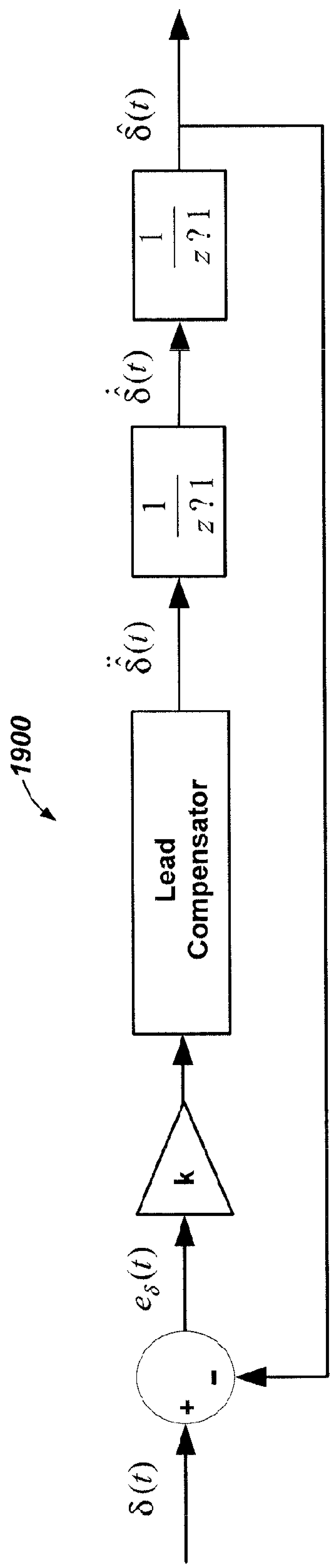

1900
δ(t)
+
-
$e_\delta(t)$
k
Lead Compensator
$\ddot{\hat{\delta}}(t)$
$\frac{1}{z?1}$
$\dot{\hat{\delta}}(t)$
$\frac{1}{z?1}$
$\hat{\delta}(t)$

FIG. 19

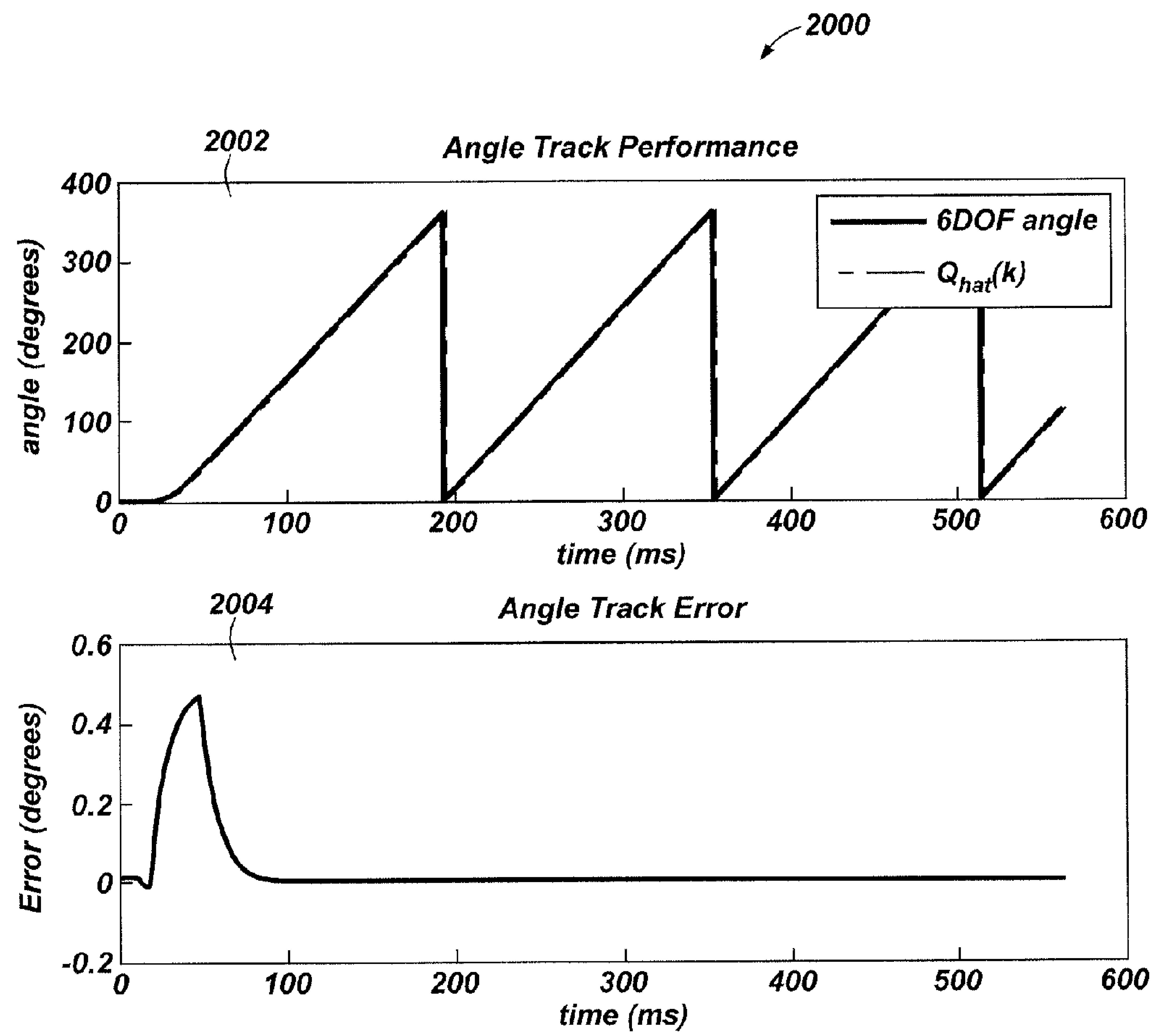

2000
2002
Angle Track Performance
angle (degrees)
400
300
200
100
0
0
100
200
300
400
500
600
time (ms)
6DOF angle
Q_hat(k)
2004
Angle Track Error
Error (degrees)
0.6
0.4
0.2
0
-0.2
0
100
200
300
400
500
600
time (ms)

FIG. 20

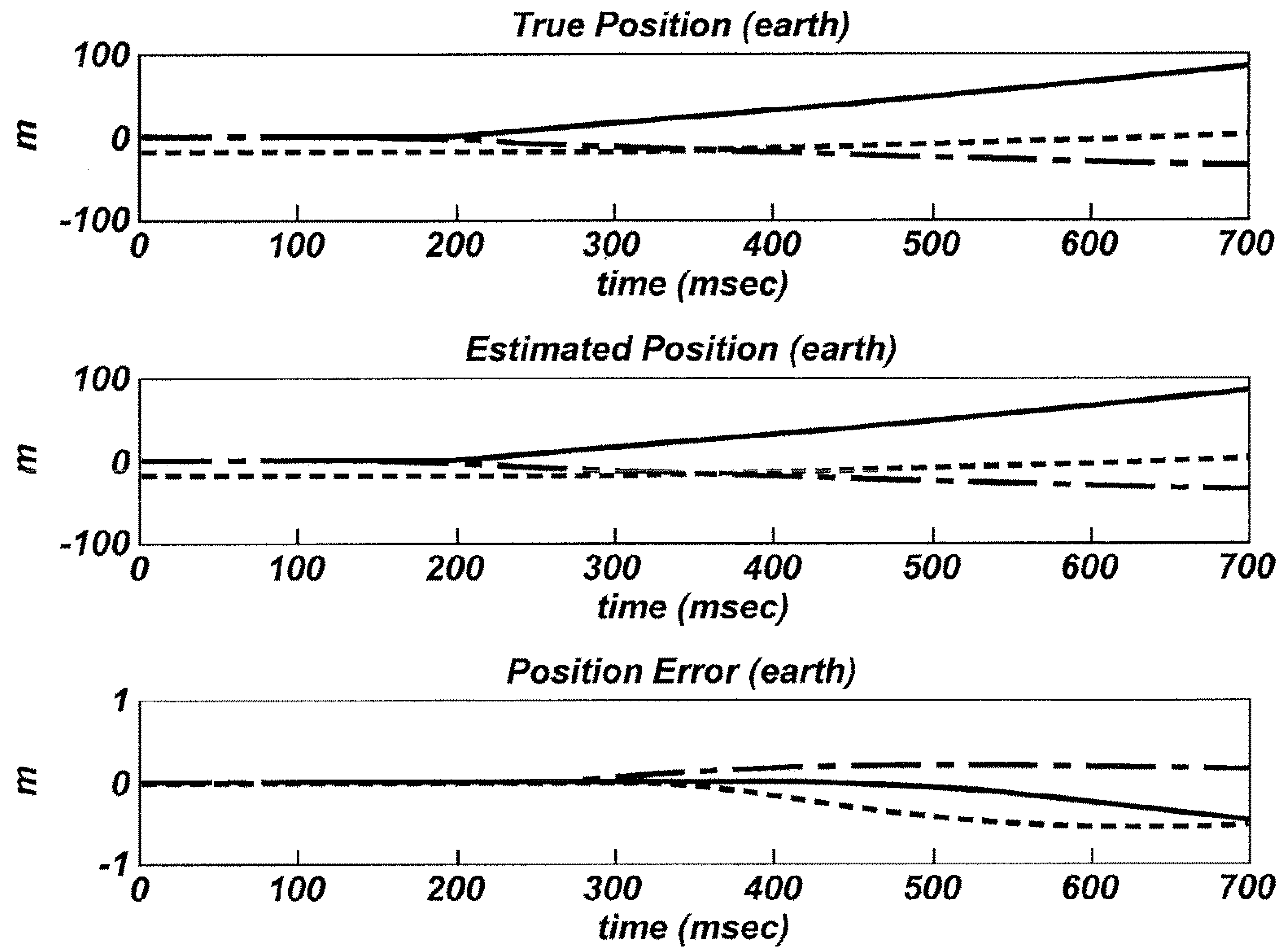

True Position (earth)
100
m
0
-100
0 100 200 300 400 500 600 700
time (msec)
Estimated Position (earth)
100
m
0
-100
0 100 200 300 400 500 600 700
time (msec)
Position Error (earth)
1
m
0
-1
0 100 200 300 400 500 600 700
time (msec)

FIG. 21

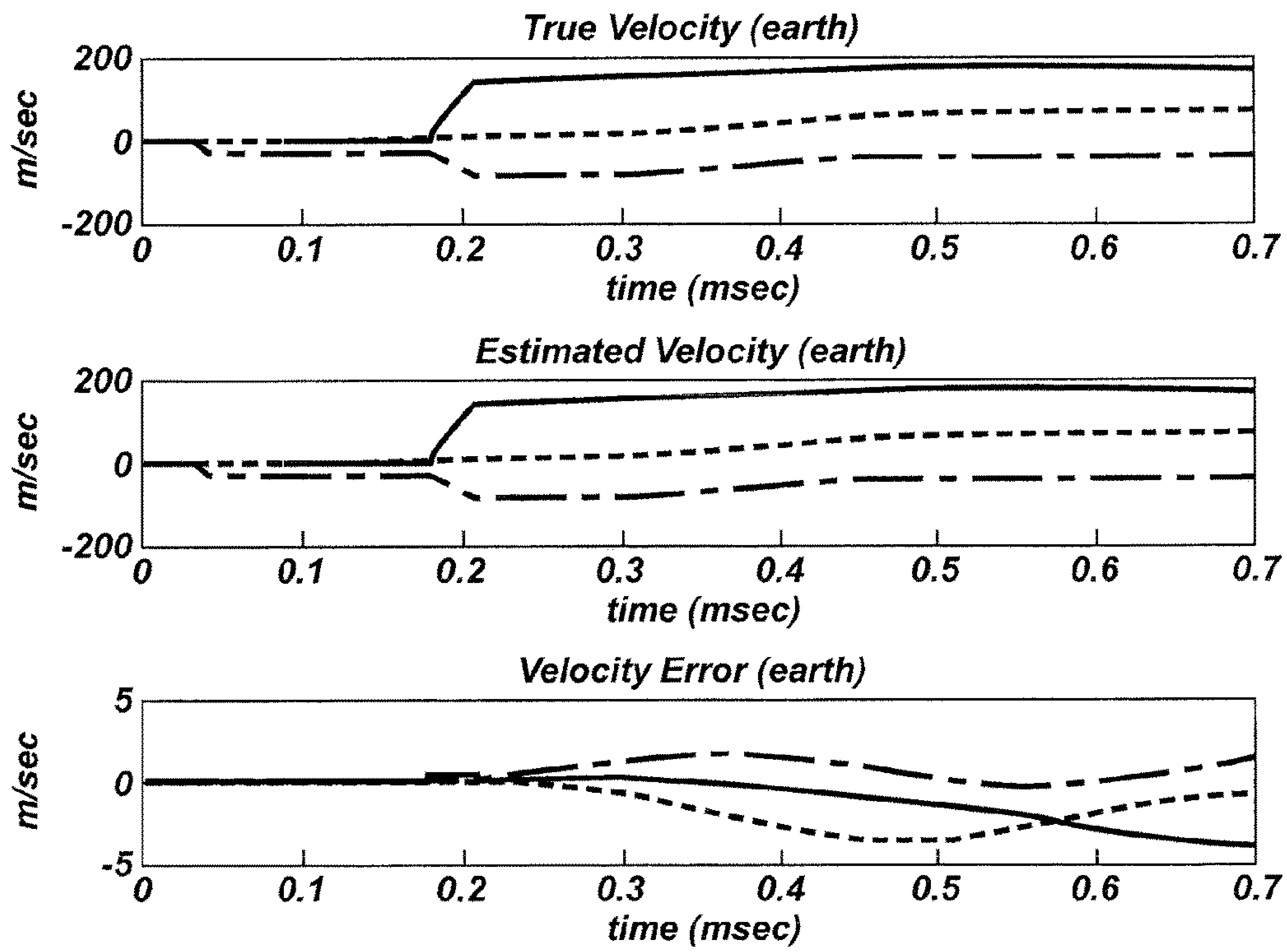

True Velocity (earth)
200
m/sec
0
-200
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
time (msec)
Estimated Velocity (earth)
200
m/sec
0
-200
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
time (msec)
Velocity Error (earth)
5
m/sec
0
-5
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
time (msec)

FIG. 22

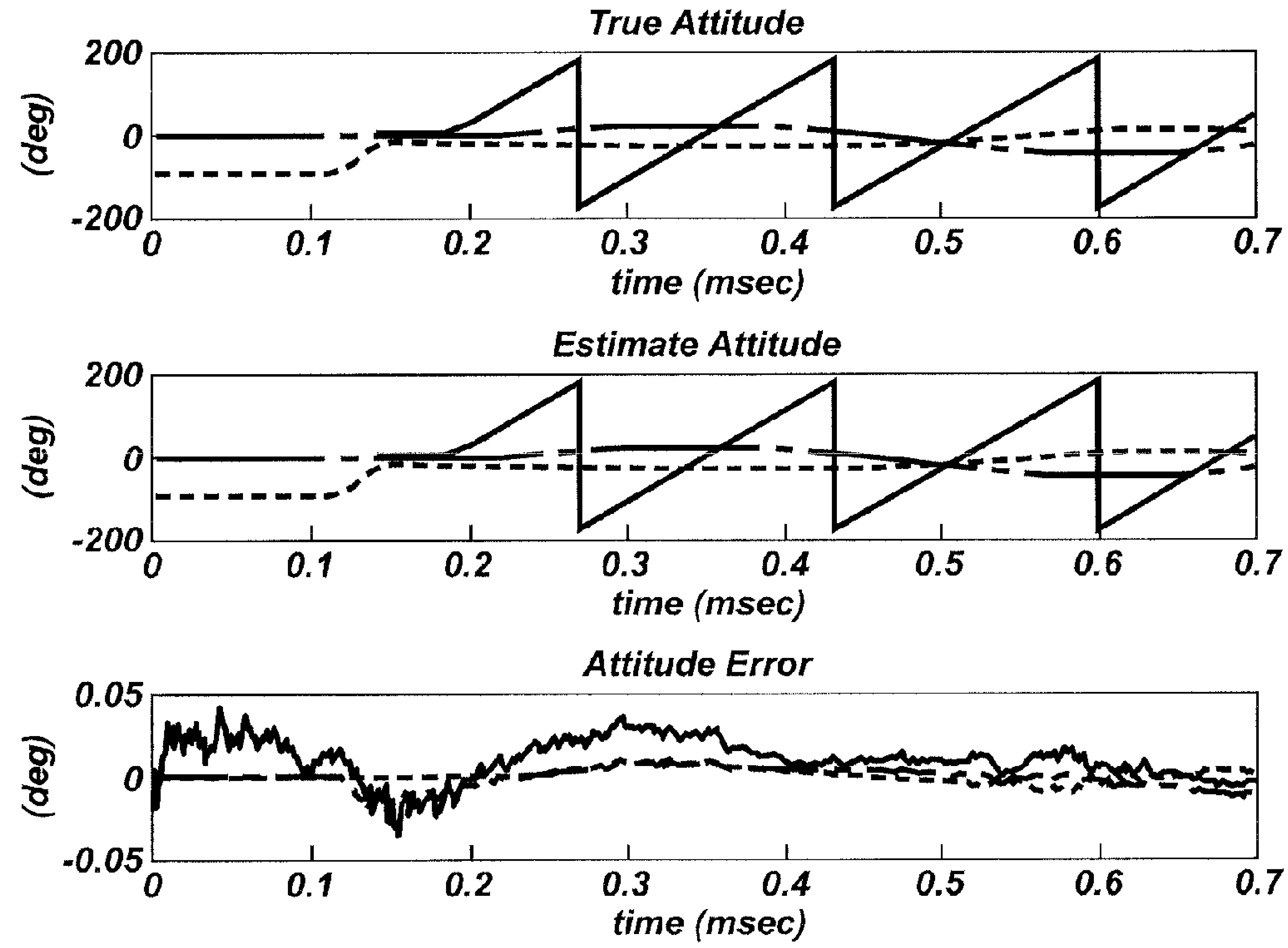

True Attitude
200
0
-200
(deg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
time (msec)
Estimate Attitude
200
0
-200
(deg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
time (msec)
Attitude Error
0.05
0
-0.05
(deg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
time (msec)

*FIG. 23*

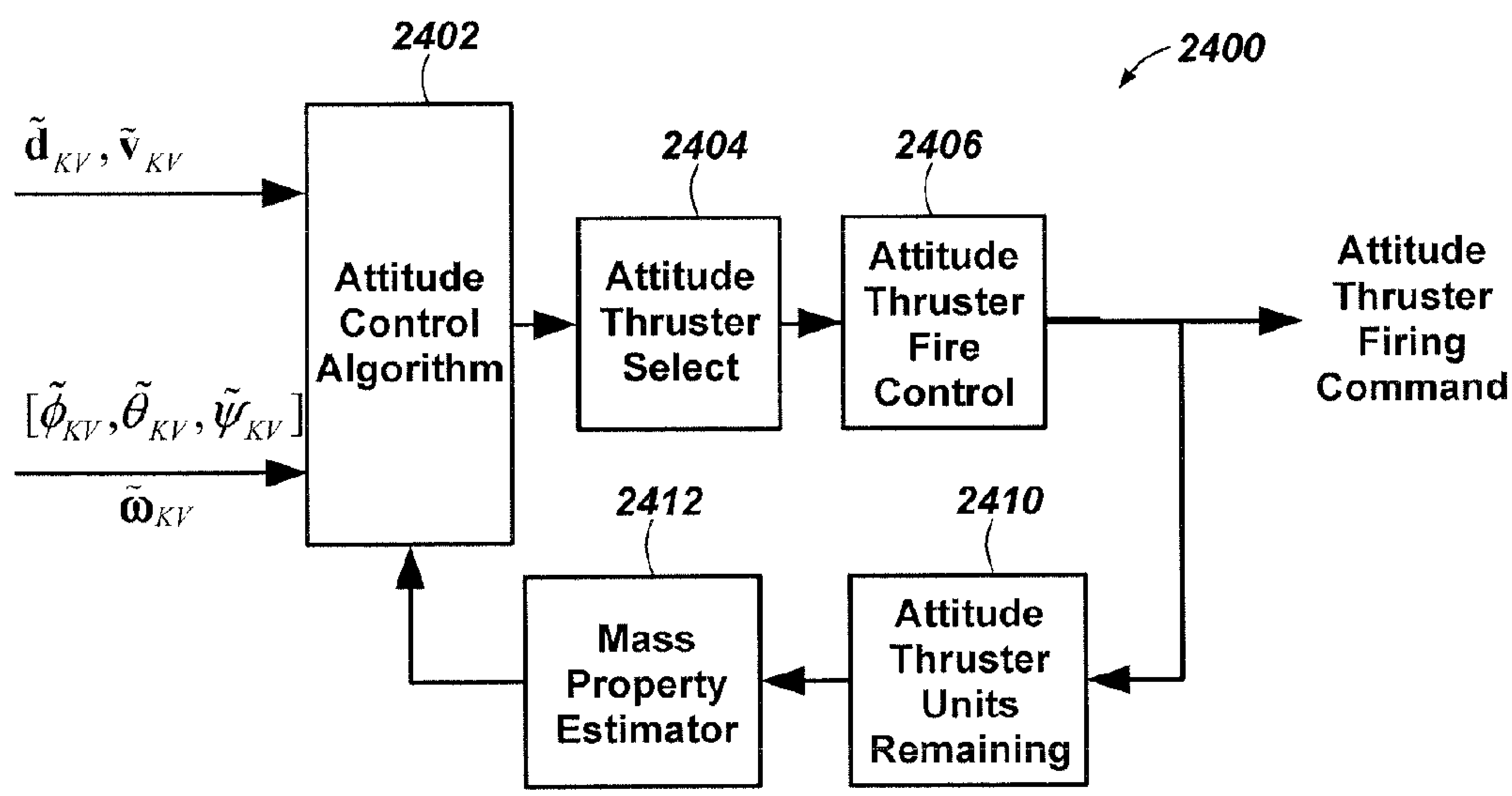

2400
2402
2404
2406
2410
2412
$\tilde{\mathbf{d}}_{KV}, \tilde{\mathbf{v}}_{KV}$
$[\tilde{\phi}_{KV}, \tilde{\theta}_{KV}, \tilde{\psi}_{KV}]$
$\tilde{\boldsymbol{\omega}}_{KV}$
Attitude Control Algorithm
Attitude Thruster Select
Attitude Thruster Fire Control
Attitude Thruster Firing Command
Attitude Thruster Units Remaining
Mass Property Estimator

*FIG. 24*

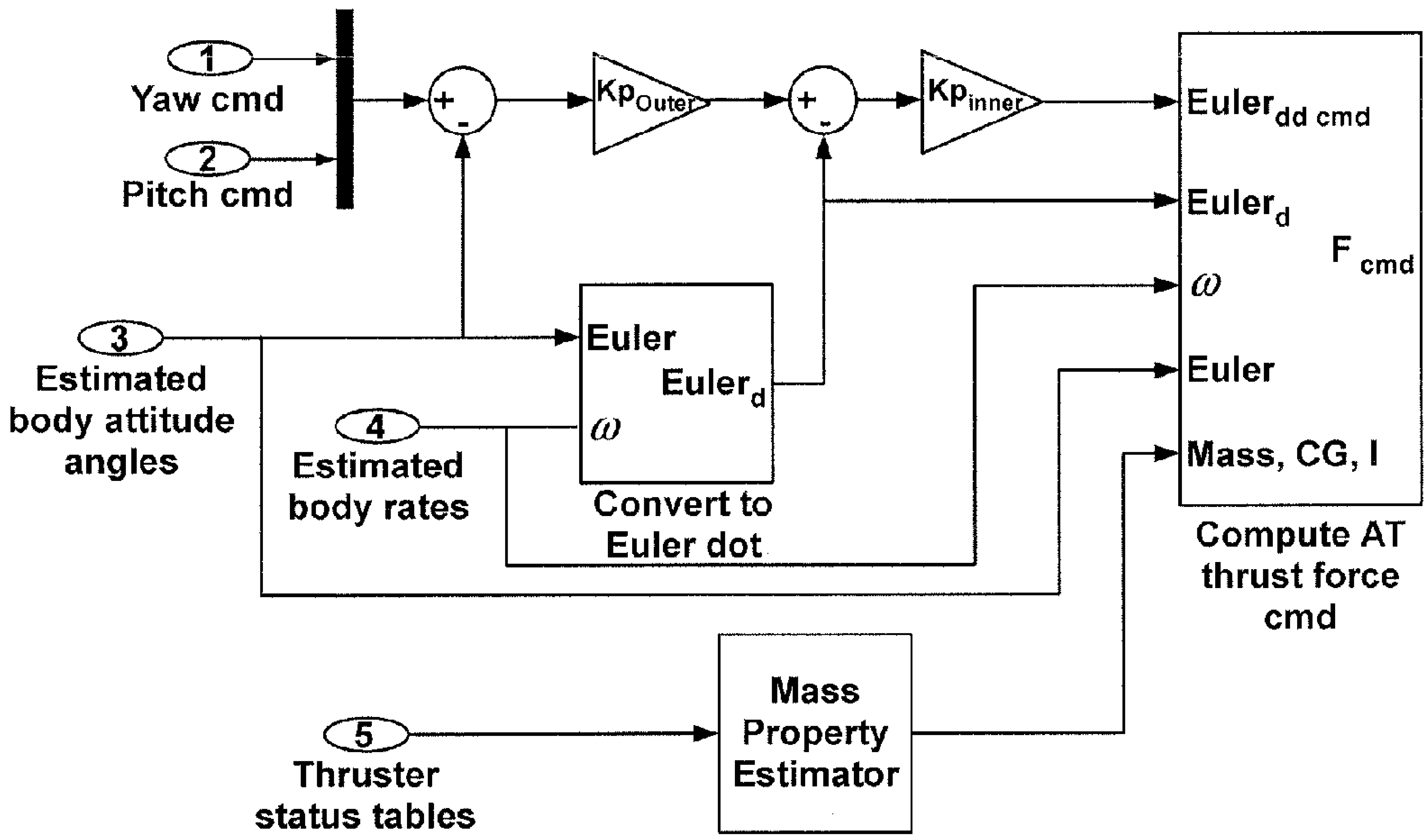
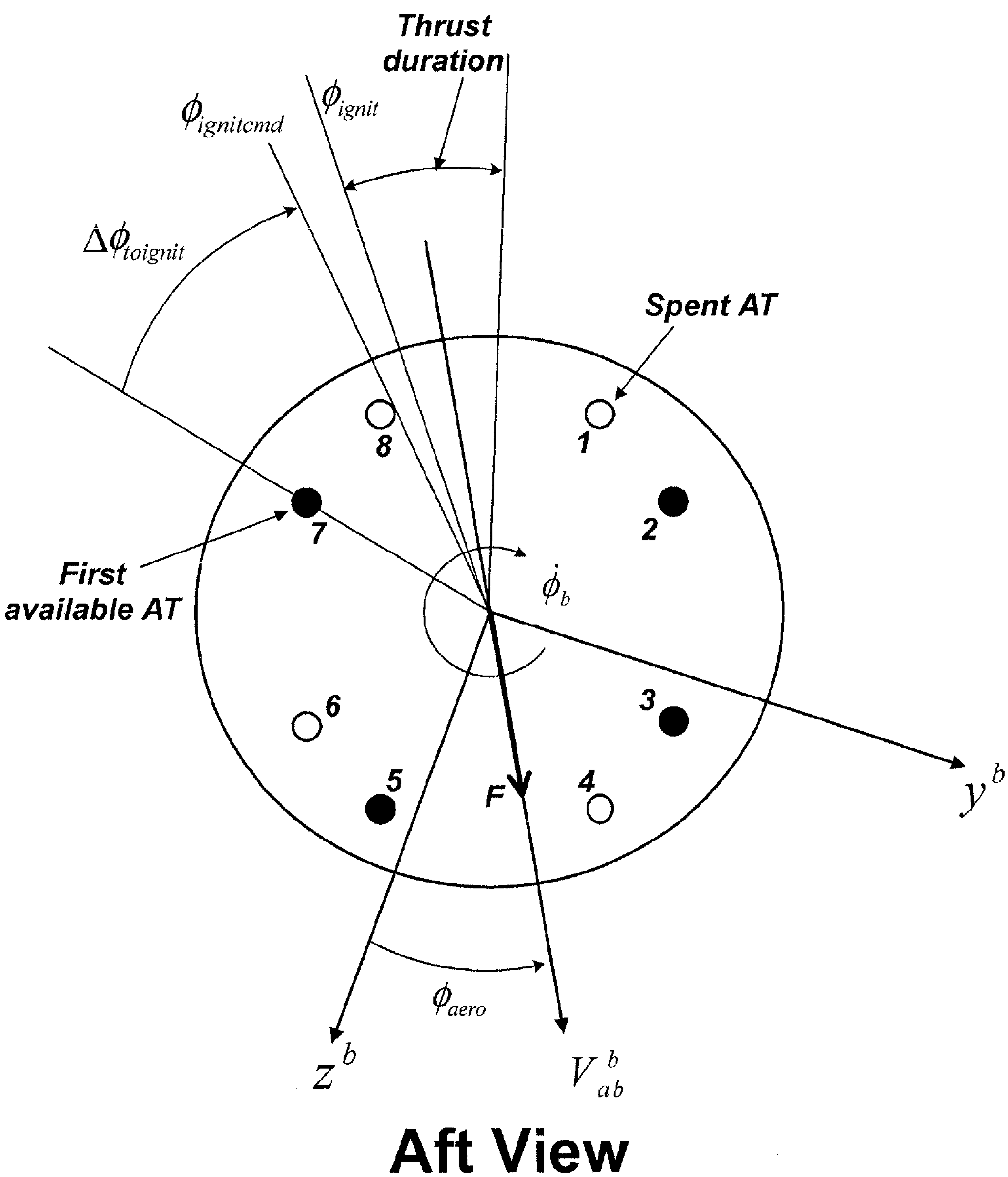

1
Yaw cmd
2
Pitch cmd
3
Estimated body attitude angles
4
Estimated body rates
5
Thruster status tables
KpOuter
KpInner
Euler
Eulerd
ω
Convert to Euler dot
Mass Property Estimator
Eulerdd cmd
Eulerd
ω
Euler
Mass, CG, I
F cmd
Compute AT thrust force cmd

*FIG. 25*



Thrust duration
$\phi_{ignitcmd}$
$\phi_{ignit}$
$\Delta\phi_{toignit}$
Spent AT
1
2
3
4
5
6
7
8
First available AT
$\dot{\phi}_b$
F
$y^b$
$\phi_{aero}$
$z^b$
$V_{ab}^b$
Aft View


*FIG. 26*

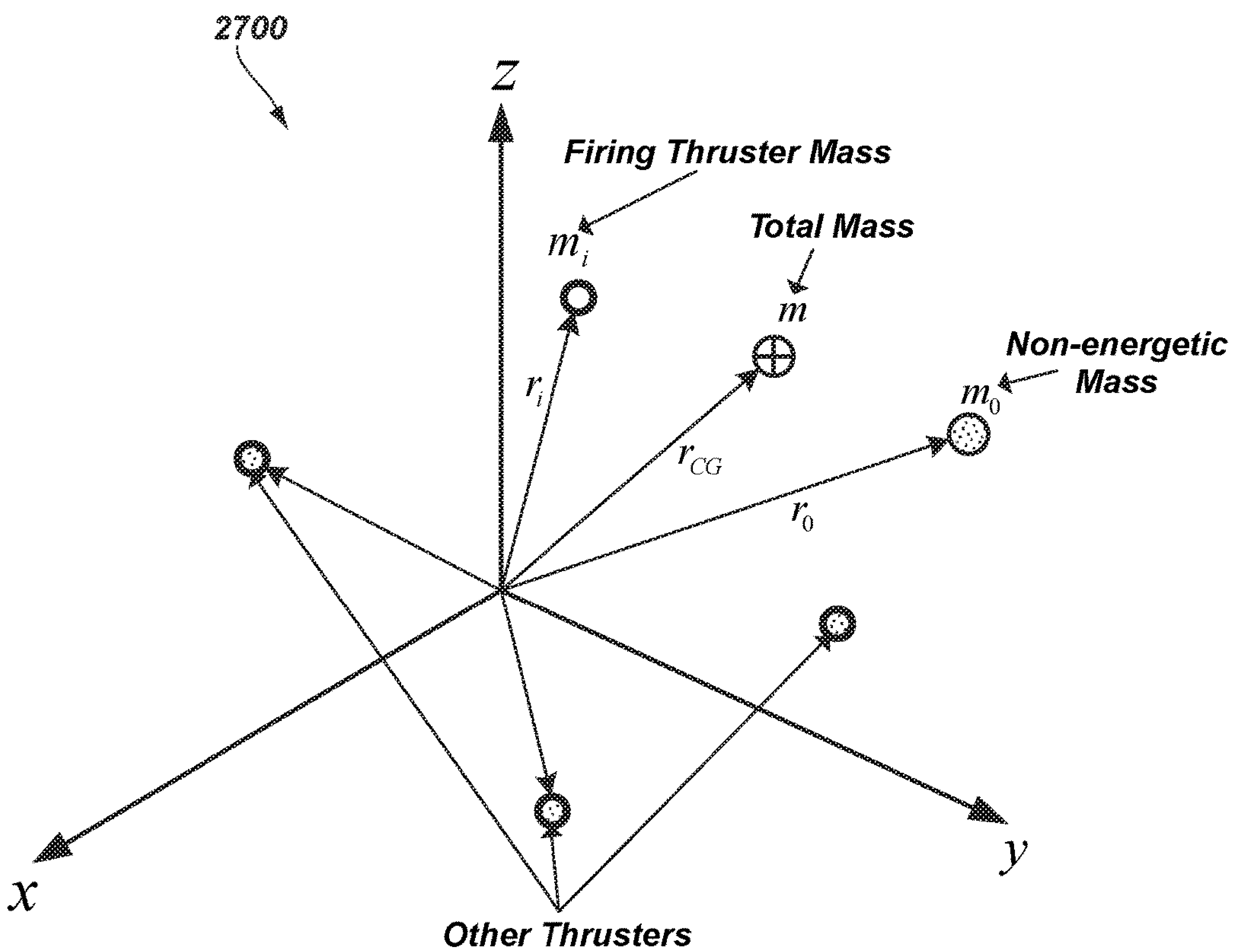

2700
Z
Firing Thruster Mass
$m_i$
Total Mass
m
Non-energetic Mass
$m_0$
$r_i$
$r_{CG}$
$r_0$
x
y
Other Thrusters

FIG. 27

# METHODS AND APPARATUSES FOR AERIAL INTERCEPTION OF AERIAL THREATS

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation-in-part of U.S. patent application Ser. No. 13/455,831, filed Apr. 25, 2012, now U.S. Pat. No. 9,170,070, issued Oct. 27, 2015, which claims priority to U.S. Provisional Patent Application Ser. No. 61/606,010, filed Mar. 2, 2012. The disclosure of each of these applications is hereby incorporated by reference in its entirety. This application is also related to U.S. patent application Ser. No. 13/839,176, filed Mar. 15, 2013, and titled "Methods and Apparatuses for Engagement Management of Aerial Threats."

## TECHNICAL FIELD

Embodiments of the present disclosure relate generally to methods and apparatuses for engagement management relative to a threat and, more particularly, to aerial interception of aerial threats.

## BACKGROUND

Rocket Propelled Grenades (RPGs) and other human carried projectiles such as Man-portable Air-Defense Systems (MANPADS or MPADS) and shoulder-launched Surface-to-Air Missiles (SAMs) represent serious threats to mobile land and aerial platforms. Even inexperienced RPG operators can engage a stationary target effectively from 150-300 meters, while experienced users could kill a target at up to 500 meters, and moving targets at 300 meters. One known way of protecting a platform against RPGs is often referred to as active protection and generally causes explosion or discharge of a warhead on the RPG at a safe distance away from the threatened platform. Other known protection approaches against RPGs and short range missiles are more passive and generally employ fitting the platform to be protected with armor (e.g., reactive armor, hybrid armor or slat armor).

Active Protection Systems (APS) have been proposed for ground vehicles for defense against RPGs and other rocket fired devices with a good success rate for quite some time. However, these systems are proposed to protect vehicles that are: 1) armored, 2) can carry heavy loads, and 3) have plenty of available space for incorporation of large critical systems. Currently these systems can weigh anywhere between 300 to 3000 lbs. and can protect the vehicle when intercepting incoming threats as close as 5 to 10 ft.

There is a need in the art for engagement management systems that can work in cooperation with intercept vehicles to engage and destroy aerial threats. There is also a need for such systems to be portable and lightweight enough for carrying on aerial and other mobile platforms that may have significant weight and size constraints, or on which an active protection system may be easily installed. There is also a need for such systems to coordinate with multiple engagements of aerial threats, intercept vehicles, and other nearby engagement management systems.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1**A and **1**B illustrate a helicopter as an aerial platform that may be under attack from an aerial threat and coverage areas that may be employed to sense when such a threat is present;



FIGS. **2**A and **2**B illustrate a conventional dispenser in which an eject vehicle (EV) according to one or more embodiments of the present disclosure may be placed;

FIG. **3** illustrates systems that may be present on a helicopter and that may intercommunicate according to one or more embodiments of the present disclosure;

FIG. **4** illustrates an exploded view of an eject vehicle showing various elements of the EV according to one or more embodiments of the present disclosure;

FIGS. **5**A-**5**C illustrate the eject vehicle of FIG. **4** as it may be configured during various stages of an intercept mission according to one or more embodiments of the present disclosure;

FIGS. **6**A-**6**C illustrate various propulsion and thruster elements that may be included with one or more embodiments of the present disclosure;

FIG. **7** illustrates various electrical and communication connections that may be present on an EV while it is disposed on the mobile platform prior to launch;

FIG. **8** is a block diagram illustrating elements that may be present on the eject vehicle according to one or more embodiments of the present disclosure;

FIG. **9**A is a block diagram illustrating elements that may be present on the aerial platform according to one or more embodiments of the present disclosure;

FIG. **9**B is a perspective view of a radar module that may be present on the aerial platform according to one or more embodiments of the present disclosure;

FIGS. **10**A and **10**B are diagrams illustrating radar scanning beams during an acquisition mode and a tracking mode, respectively;

FIG. **11** is a spectrum diagram illustrating possible Doppler spectrum regions where various aerial vehicles may be detected;

FIG. **12** is a simplified flow diagram illustrating some of the processes involved in one or more embodiments of the present disclosure;

FIG. **13** illustrates an example flight path for the eject vehicle and an aerial threat during an intercept process;

FIG. **14** illustrates two aerial vehicles flying in a formation and various radar sectors that may be covered by the aerial vehicles;

FIG. **15** is a simplified side view of a kill vehicle illustrating the principle forces of interest on the kill vehicle;

FIGS. **16**A and **16**B illustrate a nose thruster module;

FIG. **17** is a simplified block diagram of an attitude control loop;

FIG. **18** is a simplified flowchart of a Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) algorithm;

FIG. **19** illustrates the JAPRAE algorithm in the form of a conventional servo loop;

FIG. **20** illustrates a non-limiting example of a set of simulation results of the JAPRAE algorithm of FIGS. **18** and **19**;

FIG. **21** illustrates a set of position results of an Extended Kalman Filter (EKF) fusion algorithm simulation;

FIG. **22** illustrates a set of velocity results of the EKF fusion algorithm simulation of FIG. **21**;

FIG. **23** illustrates a set of attitude results of the EKF fusion algorithm simulation of FIG. **21**;

FIG. **24** illustrates an attitude control loop;

FIG. **25** illustrates a controller input-output topology;

FIG. **26** illustrates an example of a search procedure that may be used to find a thruster to fire; and

FIG. **27** illustrates a mass and center of gravity (CG) location update algorithm.

## DETAILED DESCRIPTION

In the following description, reference is made to the accompanying drawings in which is shown, by way of illustration, specific embodiments of the present disclosure. The embodiments are intended to describe aspects of the disclosure in sufficient detail to enable those skilled in the art to practice the invention. Other embodiments may be utilized and changes may be made without departing from the scope of the disclosure. The following detailed description is not to be taken in a limiting sense, and the scope of the present invention is defined only by the appended claims.

Furthermore, specific implementations shown and described are only examples and should not be construed as the only way to implement or partition the present disclosure into functional elements unless specified otherwise herein. It will be readily apparent to one of ordinary skill in the art that the various embodiments of the present disclosure may be practiced by numerous other partitioning solutions.

In the following description, elements, circuits, and functions may be shown in block diagram form in order not to obscure the present disclosure in unnecessary detail. Additionally, block definitions and partitioning of logic between various blocks is exemplary of a specific implementation. It will be readily apparent to one of ordinary skill in the art that the present disclosure may be practiced by numerous other partitioning solutions. Those of ordinary skill in the art would understand that information and signals may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof. Some drawings may illustrate signals as a single signal for clarity of presentation and description. It will be understood by a person of ordinary skill in the art that the signal may represent a bus of signals, wherein the bus may have a variety of bit widths and the present disclosure may be implemented on any number of data signals including a single data signal.

The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein may be implemented or performed with a general-purpose processor, a special-purpose processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA) or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general-purpose processor may be a microprocessor, but in the alternative, the processor may be any conventional processor, controller, microcontroller, or state machine. A general-purpose processor may be considered a special-purpose processor while the general-purpose processor is configured to execute instructions (e.g., software code) stored on a computer-readable medium. A processor may also be implemented as a combination of computing devices, such as a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

In addition, it is noted that the embodiments may be described in terms of a process that may be depicted as a flowchart, a flow diagram, a structure diagram, or a block diagram. Although a process may describe operational acts as a sequential process, many of these acts can be performed in another sequence, in parallel, or substantially concurrently. In addition, the order of the acts may be rearranged.

Elements described herein may include multiple instances of the same element. These elements may be generically indicated by a numerical designator (e.g., **110**) and specifically indicated by the numerical indicator followed by an alphabetic designator (e.g., **110**A) or a numeric indicator preceded by a "dash" (e.g., **110-1**). For ease of following the description, for the most part, element number indicators begin with the number of the drawing on which the elements are introduced or most fully discussed. For example, where feasible, elements in FIG. **3** are designated with a format of 3xx, where 3 indicates FIG. **3** and xx designates the unique element.

It should be understood that any reference to an element herein using a designation such as "first," "second," and so forth does not limit the quantity or order of those elements, unless such limitation is explicitly stated. Rather, these designations may be used herein as a convenient method of distinguishing between two or more elements or instances of an element. Thus, a reference to first and second elements does not mean that only two elements may be employed or that the first element must precede the second element in some manner. In addition, unless stated otherwise, a set of elements may comprise one or more elements.

Embodiments of the present disclosure include apparatuses and methods for providing protection for mobile platforms, such as, for example, a helicopter, from an aerial threat. Some embodiments of the present disclosure may include methods and apparatuses that are portable and lightweight enough for carrying on aerial platforms that may have significant weight and size constraints. Some embodiments of the present disclosure may include methods and apparatuses that can be incorporated into existing systems already installed on aerial platforms.

FIGS. **1**A and **1**B illustrate a helicopter as an aerial platform **100** that may be under attack from an aerial threat **120** and coverage areas **140** that may be employed to sense when such a threat is present within an intercept range (may also be referred to herein as a threat range) of embodiments of the present disclosure. As shown in FIG. **1**A, the aerial threat **120** may be shot by an attacker **110** toward the aerial platform **100**.

As used herein, "aerial threat" or "threat" are used interchangeably to refer to any threat directed toward a mobile platform, including projectiles, rockets, and missiles that may be shoulder launched or launched from other platforms. As non-limiting examples, such aerial threats include Rocket Propelled Grenades (RPGs), Man-portable Air-Defense Systems (MANPADS or MPADS), shoulder-launched Surface-to-Air Missiles (SAMs), Tube-launched, Optically tracked, Wire-guided missiles (TOWs), and other aerial weapons, having a trajectory and ordnance such that they may cause damage to the mobile platform.

The term "aerial platform" includes, but is not limited to, platforms such as helicopters, Unmanned Airborne Vehicles (UAVs), Remotely Piloted Vehicles (RPVs), light aircraft, hovering platforms, and low speed traveling platforms. The protection systems and methods of the present disclosure are particularly useful for protecting aerial platforms against many kinds of aerial threats.

While embodiments of the present disclosure may be particularly suitable for use on aerial platforms **100** due to the small size and weight, they may also be used in other types of mobile platforms like ground-based mobile platforms such as, for example, tanks, armored personnel carriers, personnel carriers (e.g., Humvee and Stryker vehicles) and other mobile platforms capable of bearing embodiments of the present disclosure. Moreover, embodiments of the present disclosure may be used for relatively stationary ground-based personnel protection wherein a mobile platform may not be involved. Accordingly, embodiments of the disclosure are not limited to aerial applications.

FIG. **1**B illustrates coverage areas **140** in which one or more embodiments of the present disclosure may detect an incoming aerial threat **120** and perform active countermeasures using one or more embodiments of the present invention to remove the aerial threat **120** before it can damage the aerial platform **100**. Some embodiments of the present disclosure may be configured such that they can be disposed in previously existing Countermeasures Dispenser Systems (CMDS).

FIGS. **2**A and **2**B illustrate a dispenser **200** configured as a conventional CMDS (e.g., an AN/ALE-47) in which an eject vehicle **400** (EV) according to one or more embodiments of the present disclosure may be placed. AN/ALE-47 dispensers are conventionally used to dispense passive countermeasures, such as, for example, radar-reflecting chaff, infrared countermeasures to confuse heat-seeking missile guidance, and disposable radar transmitters. With some embodiments of the present disclosure, eject vehicles **400** may also be placed in the AN/ALE-47 and ejected therefrom under control of the AN/ALE-47 and other electronics on the aerial platform **100** (FIGS. **1**A and **1**B). The eject vehicle **400** may be configured as a substantially cylindrical vehicle to be placed in a tubular dispenser **210** and ejection may be controlled from control wiring **220** connected to the dispenser **200**. Moreover, the dispenser **200** may be configured to hold both the passive countermeasures for which it was originally designed, as well as one or more eject vehicles **400** according to embodiments of the present disclosure.

While some embodiments of the eject vehicle **400** may be configured to be disposed in an AN/ALE-47, other types of dispensers **200** or other types of carriers for the eject vehicle **400** may also be used. Moreover, the tubular dispenser **210** is illustrated with a circular cross section. However, other cross sections may be used, such as, for example, square, hexagonal, or octagonal.

FIG. **3** illustrates systems that may be present on a helicopter frame **300** and that may intercommunicate according to one or more embodiments of the present disclosure. The helicopter frame **300** and systems described are used as specific examples to assist in giving details about embodiments of the present disclosure. In the specific example of FIG. **3**, an AAR-47 Missile Approach Warning System (MAWS) warns of threat missile approaches by detecting radiation associated with the missile. In the specific example, four MAWSs (**320**A, **320**B, **320**C, and **320**D) are disposed near four corners of the helicopter frame **300**. A central processor **360** may be used to control and coordinate the four MAWSs (**320**A, **320**B, **320**C, and **320**D).

Two AN/ALE-47 dispensers (**200**A and **200**B) are positioned on outboard sides of the helicopter frame **300**, each of which may contain one or more eject vehicles **400**. As shown in FIG. **3**, there are four eject vehicles **400** on each side labeled EV**1** through EV**4** on one side and labeled EV**5**-EV**8** on the other side. The AN/ALE-47 dispensers (**200**A and **200**B) are each controlled by an AN/ALE-47 sequencer (**350**A and **350**B), which are, in turn, controlled by the central processer **360**.



According to one or more embodiments of the present disclosure four radar modules (**900**A, **900**B, **900**C, and **900**D) are included to augment and connect with the AAR-47s and communicate with the eject vehicles **400**. These radar modules **900** (see FIG. **9**A) are configured to detect and track relatively small incoming aerial threats (e.g., an RPG) as well as the outgoing eject vehicles **400**. Moreover, the radar modules **900** can send wireless communications (**340**A, **340**B, **340**C, and **340**D) to the eject vehicles **400** both before and after they are ejected from the dispensers (**200**A and **200**B). The radar modules **900**, and eject vehicles **400** may each include unique identifiers, such as, for example, a Media Access Control (MAC) address. The radar modules **900** may also be configured to detect, track, and communicate with other friendly platforms such as, for example, other helicopters flying in formation with the helicopter. Thus, all helicopters within communication range can communicate and share radar and control information to form a broad coverage area, similar to cellular telephone base station coverage. Moreover, and as explained more fully below, the helicopters may communicate to define different sector coverage areas such that one helicopter does not launch an eject vehicle **400** into a sector that may damage or interfere with another helicopter.

The control processors, such as the central processor **360**, the MAWSs **320**, the radar modules **900**, the sequencers **350**, and the dispensers **200** may be configured to form an ad hoc network and include the eject vehicles **400**.

The specific example of FIG. **3** is shown to illustrate how radar modules (**900**A-**900**D) and eject vehicles (EV**1**-EV**8**) of the present disclosure can be incorporated with existing systems on helicopter platforms with little change. Of course, other systems may be employed with embodiments of the present disclosure. As a non-limiting example, one radar **900**A may be positioned on one side of the helicopter frame **300** and another radar module **900**C may be positioned on another side of the helicopter frame. In such a case, the radar modules **900** would be configured to provide hemispherical coverage areas. These radar modules **900** may be controlled by, communicate with, or a combination thereof, a different central processor **360** configured specifically for embodiments of the present disclosure. Moreover, the eject vehicles **400** may be disposed in different carriers or different dispensers from the AN/ALE-47 dispensers (**200**A and **200**B) shown in FIG. **3**.

When embodiments of the present disclosure are used as illustrated in FIG. **3**, they provide an ultra-lightweight active protection system for helicopter platforms that may increase the survivability against RPG attacks to better than 90% for RPGs fired from ranges as close as about 100 meters away.

In order to satisfy the helicopter platform constraints, embodiments of the present disclosure address many significant technology areas:

1) For helicopter applications, size, weight, and power should be considered. Every pound of added airframe equipment will reduce capacity to carry personnel or cargo, and the space for adding equipment to the airframe may be at a premium. At least some embodiments of the present disclosure are configured to be less than about 50 pounds and occupy about 5.5"×5.5" surface area at each of the four corners of a helicopter exterior shell and with minimal impact to existing wiring kits.

2) Helicopters generally do not carry armor and thus, the intercept of an incoming threat (e.g., an RPG) must occur at a range that is safe to the un-armored helicopter airframe. Using an RPG-7 as an example, to achieve a survival probability of about 99% from the blast alone, the intercept

should occur at distances beyond 30 meters from the helicopter shell. This requirement significantly influences the system response time, when considering that an RPG fired at a 100-meter distance may impact the helicopter in less than about 600 milliseconds.

3) A third concern is fratricide and collateral damage to friendly forces that may be amplified by the helicopter platform deploying kinetic countermeasures in a position above ground and potentially next to a wingman helicopter or in the vicinity of civilians, friendly troops, or a combination thereof. Some embodiments of the present disclosure are configured to work in combination with embodiments on other helicopters when the helicopters are flying in formation relatively close to each other.

4) Some embodiments of the present disclosure can geo-locate the attacker **110** (FIG. **1**A) after a few radar track frames are processed.

5) Embodiments of the present disclosure can engage multiple threats at a time. In other words, multiple incoming aerial threats **120** can be detected and tracked and multiple outgoing eject vehicles **400** can be tracked. In addition, to increase a probability of destroying an incoming aerial threat **120**, multiple eject vehicles **400** may be launched, directed toward, and detonated proximate the same aerial threat **120**.

6) Finally, eject vehicles **400** can be launched and guided to the point of attack with the same or different warheads and detonated above the threat point of origin.

To address these technology areas, some embodiments of the present disclosure include an active kinetic countermeasure projectile (i.e., the eject vehicle **400** of FIG. **2**B), including an ejection mechanism with an impulse charge that can fit in, and can be launched by, the AN/ALE-47 chaff/flare dispenser **200**. Some embodiments of the present disclosure include the radar module **900** covering a 90 degree sector or more (i.e., with a 90 degree sector, each helicopter platform would use four radar modules **900**).

When referring to the radar module **900** herein (e.g., as shown in FIG. **3**), it should be understood that in some embodiments the radar module **900** may perform the operations described herein in combination with other electronics and processors on the aerial platform **100**. As such, the radar modules **900** may be used to: 1) search, acquire, and track incoming aerial threats **120**, 2) launch the active kinetic countermeasure (i.e., eject vehicle **400**), 3) track the outgoing eject vehicle **400** with respect to the incoming aerial threat **120**, 4) point and guide the eject vehicle **400** toward the incoming aerial threat **120**, 5) command detonate the eject vehicle **400**, and 6) geo-locate the attacker **110**, all in less than about one second. In one configuration, at least two AN/ALE-47 dispensers **200** would be used in conjunction with the four radar modules **900** such that each dispenser **200** provides hemispherical coverage.

The radar modules **900** may be configured as pulse Doppler radar modules **900** to scan the azimuth plane and the elevation plane using two orthogonal fan beams and may be configured to cover a 90 degree sector in about 20 milliseconds. Upon detecting an incoming aerial threat **120**, the associated radar module **900** may then direct the launch and guidance of an eject vehicle **400** from an AN/ALE-47 dispenser **200** that covers that sector. The eject vehicle **400** may be command guided to the target by the radar module **900** and command detonated. The radar modules **900** may be configured as an addition to the existing AN/AAR-47 system and may use its existing interface for launching of the eject vehicle **400**.

Some of the embodiments of the present disclosure may be configured to deploy an eject vehicle **400** that fits in a standard dispenser **200** but could be stabilized and pointed towards the threat after launch, in less than about 50 milliseconds, in the rotor downwash of a helicopter, and when ejected in the fixed direction dictated by the dispenser **200**. The radar modules **900** may then guide the eject vehicle **400** to accurately intercept the aerial threat **120** within about 330 milliseconds and thus reduce the requirement of carrying a large warhead.

FIG. **4** illustrates an exploded view of an eject vehicle **400** showing various elements of the eject vehicle **400** according to one or more embodiments of the present disclosure. Reference may also be made to FIGS. **1A-3** in describing features and operations of the eject vehicle **400**. The eject vehicle **400** is a lightweight guided projectile that, in some embodiments, may be designed to be launched from chaff/flare dispensers. The eject vehicle **400** may intercept and destroy incoming aerial threats **120** at ranges sufficient to prevent damage to the host aerial platform **100**. The eject vehicle **400** may be packaged in a cartridge containing an impulse charge and interface electronics designed to fit the AN/ALE-47 dispenser magazine.

The eject vehicle **400** includes an ejection piston **780** configured to transmit the energy of an impulse cartridge **750** (described below in connection with FIG. **7**) to the eject vehicle **400** and launch the eject vehicle **400** away from the aerial platform **100** to a distance safe enough for the eject vehicle **400** to begin performing alignment and interception maneuvers.

A rocket motor **420** may be used to propel the eject vehicle **400** toward the aerial threat **120** after the eject vehicle **400** has been rotated such that a longitudinal axis of the eject vehicle **400** is pointed in the general direction of the aerial threat **120**. A first set of folding fins **482** may be attached to the rocket motor **420** and configured to deploy once the eject vehicle **400** has exited the dispenser **200**. The folding fins **482** are small and configured to provide stability to the eject vehicle **400** during its flight path rather than as control surfaces for directing the fight path.

An airframe shell **430** may be configured to contain a warhead **440**, a divert thruster module **610**, a nose thruster module **620** (may also be referred to herein as an alignment thruster module **620**), an electronics module **450**, and a battery **452**. An airframe nose **490** may be configured to attach to the airframe shell **430** to protect the electronics module **450** and provide a somewhat aerodynamic nose for the eject vehicle **400**.

A safe and arm module **460** may be included within the airframe shell **430** and configured to safely arm the warhead **440** when the eject vehicle **400** is a safe distance away from the aerial platform **100**.

FIGS. **5A-5C** illustrate the eject vehicle **400** of FIG. **4** as it may be configured during various stages of an intercept mission according to one or more embodiments of the present disclosure. Stage **1**, in FIG. **5**A, illustrates the eject vehicle **400** in a cartridge **710** (FIG. **7**) and includes the ejection piston **780**, the rocket motor **420**, the airframe shell **430**, and the airframe nose **490**.

Stage **2**, in FIG. **5**B, illustrates the eject vehicle **400** after it has been dispensed and shows the rocket motor **420**, the airframe shell **430**, and the airframe nose **490**. FIG. **5**B also illustrates the folding fins **482** deployed near the end of the rocket motor **420** and wireless communication antennas **890** deployed near the airframe nose **490**.

Stage **3**, in FIG. **5**C illustrates the eject vehicle **400** after the rocket motor **420** has burned and been detached from the airframe shell **430**. At this stage, the eject vehicle **400** may be referred to as a terminal vehicle and includes the airframe nose **490**, the wireless communication antennas **890**, and the airframe shell **430**. Still within the airframe shell **430** are the warhead **440**, the divert thruster module **610**, the alignment thruster module **620**, the electronics module **450**, the battery **452**, and the safe and arm module **460**. After the rocket motor **420** is detached, a second set of folding fins **484** are deployed from the airframe shell **430** to stabilize the eject vehicle **400** during the remainder of the flight to intercept the aerial threat **120**. This second set of folding fins **484** are used to replace the first set of folding fins **482** that were attached to the rocket motor **420**, which has been detached from the airframe shell **430** during stage **3**.

In addition, after the rocket motor **420** is detached, one or more corner reflectors **470** are exposed. The corner reflector **470** may be configured with sharp angles to enhance radar detection of the eject vehicle **400** by a radar module **900** on the aerial platform **100**. For example, the corner reflector **470** may be configured as an interior angle of a small cube shape, which will enhance radar detection.

Returning to FIG. **4**, the alignment thruster module **620** is offset from a center of mass of the eject vehicle **400** such that an initial pitch maneuver can be performed to align the longitudinal axis of the eject vehicle **400** along an intercept vector pointed toward the aerial threat **120**. This alignment maneuver is performed prior to the burn of the rocket motor **420**.

The divert thruster module **610** is positioned substantially near a center of mass of the terminal vehicle and is used to laterally divert the terminal vehicle from its current flight path to make minor corrections to the flight path in order to more accurately intercept the aerial threat **120**. The terminal vehicle may be referred to herein as the eject vehicle **400** and it should be understood what is being referred to based on the context of the discussion.

The warhead **440** may be command detonated when the radar module **900** on the aerial platform **100** determines that the eject vehicle **400** has reached the closest point of approach (nominally about 15 cm). The use of thrusters, provide the fast reaction times that may be needed to intercept the aerial threat **120** at a nominal distance of about 50 meters when the aerial threat **120** is launched from a range of about 100 meters.

FIGS. **6A**-**6C** illustrate various propulsion and thruster elements that may be included with one or more embodiments of the present disclosure. FIG. **6A** illustrates a nose thruster module **620** with four nose thrusters **622** (two are hidden) arranged around a periphery of the nose thruster module **620**. These nose thrusters **622** (also referred to herein as alignment thrusters **622**) are positioned to generate a perpendicular force on the eject vehicle **400** relative to the longitudinal axis and are offset from the center of mass of the eject vehicle **400** so that an initial pitch maneuver can be performed to rotate and align the longitudinal axis of the eject vehicle **400** along an intercept vector pointed toward the aerial threat **120**. In this embodiment, the four nose thrusters **622** are orthogonally arranged giving two opportunities to adjust the pitch of the eject vehicle **400** in each direction. Of course, other embodiments may include fewer or more alignment thrusters **622**.

FIG. **6B** illustrates a divert thruster module **610** with eight divert thrusters **612** (five are hidden) arranged around a periphery of the divert thruster module **610**. These divert thrusters **612** are positioned to generate a perpendicular force on the eject vehicle **400** relative to the longitudinal axis and are positioned near the center of mass of the eject vehicle **400** so that the divert thrusters **612** will move the eject vehicle **400** laterally to a slightly different travel path, while substantially maintaining the same pitch. Thus, the divert thrusters **612** can modify the flight path of the eject vehicle **400** to correct for minor errors in the initial pitch maneuvers pointing directly toward the aerial threat **120**. In this embodiment, eight divert thrusters **612** are used giving eight opportunities to adjust the flight path of the eject vehicle **400** during its flight toward the aerial threat **120**. Of course, other embodiments may include fewer or more divert thrusters **612**.

FIG. **6C** illustrates a thruster **650** configured to expel a gas through a nozzle **652** to create a lateral force. The thruster **650** may be controlled from a thrust signal **654**, which may be connected to the electronics module **450** of the eject vehicle **400**. The thruster **650** is one example of a type of thruster that may be used for both the divert thrusters **612** and the alignment thrusters **622**.

FIG. **7** illustrates various electrical and communication connections that may be present on the eject vehicle **400** while it is disposed on the aerial platform **100** (FIGS. **1A** and **2B**) prior to launch. A cartridge **710** includes a cartridge flange **720** such that the cartridge **710** may be securely placed in a dispenser **200** (FIG. **2A**). An end cap **790** may be positioned over the cartridge **710** to hold the eject vehicle **400** within the cartridge **710**. An impulse cartridge **750** is positioned near the base of the cartridge flange **720** and is configured to fire in response to a fire command signal **755** from the radar module **900** (FIG. **3**) or other electronics on the aerial platform **100**. An ejection piston **780** is positioned between the impulse cartridge **750** and the eject vehicle **400** and is configured to transmit the energy of the firing impulse cartridge **750** to the eject vehicle **400** and propel the eject vehicle **400** out of the dispenser **200** and safely away from the aerial platform **100**.

A power signal **740** and a ground signal **730** may run along or through the cartridge to an antenna spring contact **745** and a ground spring contact **735**, respectively. The ground spring contact **735** is configured to flexibly couple with a ground patch **738** on the eject vehicle **400** to provide a ground for the eject vehicle **400** electronics while the eject vehicle **400** is in the cartridge **710**. The antenna spring contact **745** is configured to flexibly couple with the antenna **890** on the eject vehicle **400** and a power signal on the eject vehicle **400** to provide power and direct communication for the eject vehicle **400** electronics while the eject vehicle **400** is in the cartridge **710**. The cartridge **710** may include a cartridge antenna **760** that may be coupled to the antenna **890** of the eject vehicle **400** by the antenna spring contact **745**. Thus, the eject vehicle **400** may communicate wirelessly **795** with electronics onboard the aerial platform **100** through the antenna **890** on the eject vehicle **400** or through the cartridge antenna **760**.

FIG. **8** is a block diagram illustrating elements that may be present on the eject vehicle **400** according to one or more embodiments of the present disclosure. A microcontroller **810** may be coupled to a memory **820**, which is configured to hold instructions for execution by the microcontroller **810** and data related to command and control of the eject vehicle **400**. The microcontroller **810** may be any suitable microcontroller, microprocessor, or custom logic configured to directly execute, or execute responsive to software instructions, processes related to operation of the eject vehicle **400**. The memory **820** may be any suitable combination of volatile and non-volatile memory configured to hold data and computing instructions related to operation of the eject vehicle **400**.

One or more antennas **890** may be configured to provide a communication link with electronics (e.g., the radar module **900**) onboard the aerial platform **100**. As non-limiting examples, the communication link may be configured using WiFi or WiMax frequencies and protocols. A diversity combiner **880** may be used to combine signals from multiple antennas.

A communication transceiver **870** (e.g., a WiFi transceiver) may be coupled to the diversity combiner **880** and be configured to transmit and receive frequencies to and from the diversity combiner **880**. A communication modem **860** (e.g., a WiFi modem) may be coupled to the communication transceiver **870** and be configured to package and modulate communication information for communication transmission as well as demodulate and extract information from communication reception. The microcontroller **810** receives information from the communication modem **860** and may perform operations related to the received information. In addition, based on processes performed on the microcontroller **810**, information may be sent to the communication modem **860** for transmission through the one or more antennas **890**.

The microcontroller **810** may be coupled to a thrust controller **830**, which interfaces with the alignment thrusters **622** and the divert thrusters **612** (FIGS. **6**A and **6**B). A warhead fuzing interface **840** may be provided to interface to the warhead **440** (FIG. **4**), the safe and arm module **460** (FIG. **4**) or a combination thereof, for arming and control of detonation of the warhead **440**.

A roll sensor **850** and a vertical reference **855** may be used in combination to determine the attitude of the eject vehicle **400** as well as a spin rate and spin position of the eject vehicle **400** and communicate such information to the microcontroller **810**. Other types of sensors, such as, for example, accelerometers and magnetometers may also be used for this purpose.

FIG. **9**A is a block diagram illustrating elements that may be present on the aerial platform **100** according to one or more embodiments of the present disclosure. The electronics module and functions thereof on the aerial platform **100** may be contained within a radar module **900**, as illustrated in FIG. **9**B. Alternatively, some of the function may be within the radar module **900** while other functions may be located in different places on the aerial platform **100** such as, for example, the central processor **360** (FIG. **3**). The various modules used to control the radar module **900** and the eject vehicle **400** and determine other information related thereto may be collectively referred to herein as an "onboard system".

FIG. **9**B is a perspective view of the radar module **900** that may be present on the aerial platform **100** according to one or more embodiments of the present disclosure. The radar module **900** includes an azimuth scan radar antenna **920**, an elevation scan radar antenna **940**, and a wireless communication link antenna **960**.

The azimuth scan radar antenna **920** is included in an azimuth radar subsystem, which includes a diplexer **922** for combining radar sent and reflected radar received. A Radio Frequency (RF) up/down converter **925** converts the radar frequencies sent from a digital synthesizer **930** and converts the radar frequencies received for use by a digital receiver **935**.

The elevation scan radar antenna **940** is included in an elevation radar subsystem similar to the azimuth radar subsystem, but configured for the elevation direction. The elevation radar subsystem includes a diplexer **942** for combining radar sent and reflected radar received. A Radio Frequency (RF) up/down converter **945** converts the radar frequencies sent from a digital synthesizer **950** and converts the radar frequencies received for use by a digital receiver **955**.

The wireless communication link antenna **960** may be configured to provide a communication link with electronics onboard the eject vehicle **400**. As non-limiting examples, the communication link may be configured using WiFi or WiMax frequencies and protocols. A wireless communication subsystem includes a communication transceiver **965** (e.g., a WiFi transceiver) coupled to the wireless communication link antenna **960** and configured to transmit and receive frequencies to and from the antenna **960**. A communication modem **970** (e.g., a WiFi modem) may be coupled to the communication transceiver **965** and be configured to package and modulate communication information for communication transmission as well as demodulate and extract information from communication reception.

A sector processor **910** communicates with the elevation radar subsystem, the azimuth radar subsystem, and the wireless communication subsystem. The sector processor **910** may communicate helicopter navigation information **912** from other electronics on the aerial platform **100**. Referring also to FIG. **3**, the sector processor **910** may also communicate with the dispenser **200** (e.g., one or more ALE-47s) using communication signal **914** and the Missile Approach Warning System **320** (e.g., one or more AAR-47s) using communication signal **916**. The sector processor **910** performs a number of functions to detect and track aerial threats **120**, control and track the eject vehicle **400**, as well as other functions related to the active protection system. In some embodiments, communication between the dispenser **200** and the sector processor **910** may be accomplished through the Missile Approach Warning System **320**.

The sector processor **910** in combination with the radar subsystems can detect and track incoming aerial threats **120** (e.g., RPGs). Based on the tracking of the incoming aerial threat **120**, and in combination with navigation information from the aerial platform **100**, the sector processor **910** can extrapolate to a geo-location of the attacker **110**, from where the aerial threat **120** was launched. The aerial platform **100** may act on this geo-location or transmit the geo-location to other aerial platforms or ground-based platforms for follow-up actions.

The sector processor **910** may be configured to send launch commands to the dispenser **200** on communication signal **914** to launch one or more eject vehicles **400** to intercept one or more detected aerial threats **120**. The sector processor **910** may also calculate required pitch adjustments that should be performed by the eject vehicle **400** after it has been ejected and is safely away from the aerial platform **100**.

Once the eject vehicle **400** is launched, the sector processor **910** may be configured to track the eject vehicle **400** and send guidance commands (i.e., divert commands) to the eject vehicle **400** so the eject vehicle **400** can perform divert maneuvers to adjust its flight path toward the aerial threat **120**. The sector processor **910** may also be configured to determine when the eject vehicle **400** will be near enough to the aerial threat **120** to destroy the aerial threat **120** by detonation of the warhead **440** on the eject vehicle **400**. Thus, a detonation command may be sent to the eject vehicle **400** instructing it to detonate, or instructing it to detonate at a detonation time after receiving the command.

FIGS. **10**A and **10**B are diagrams illustrating radar scanning beams during an acquisition mode and a tracking mode, respectively. Referring to FIGS. **10**A, **10**B, **9**, and **3**, the radar modules **900** may be mounted in close proximity to the existing AN/ALR-47 missile warning receiver (MWR) installations to provide 360 degrees spatial coverage while minimizing wiring modifications to the helicopter. It is anticipated that an aerial threat **120** will be launched at relatively short ranges, typically on the order of 100 m. The radar modules **900** are designed to detect and track the low radar cross section (typically −15 dBsm) of an RPG fired from any aspect angle, within 30 milliseconds of launch, and out to a range of at least 300 meters. The radars operate in the Ka-Band to minimize the antenna size yet provide the precision angular measurements needed to guide the eject vehicle **400** to intercept the aerial threat **120**. A high pulse-repetition-frequency pulse Doppler waveform provides radial velocity measurements as well as the clutter rejection needed to operate in close proximity to the ground while detecting low radar cross section targets. Pulse compression may be used to achieve precision range measurements as well as increasing the transmit duty cycle to best utilize the capabilities of existing Ka-Band solid-state power amplifiers. The antennas generate a pair of orthogonal fan beams, providing a continuous track-while-scan capability to minimize detection latency and provide multiple target track capability. Beam scanning can be accomplished using a frequency scan method to eliminate the need for expensive phase shifters.

FIG. **10**A illustrates an acquisition mode wherein an elevation radar generates an elevation fan beam extending in the vertical direction that sweeps in the horizontal direction and an azimuth radar generates an azimuth fan beam extending in the horizontal direction that sweeps in the vertical direction. Thus, an entire 90-degree scan sector can be covered by the radar systems to quickly detect and acquire an incoming aerial threat **120** when it is within range.

FIG. **10**B illustrates a track mode. In FIG. **10**B, two sequential azimuth scans and two sequential elevation scans are shown that pinpoint a first location **1010** of the eject vehicle **400**. In addition, two sequential azimuth scans and two sequential elevation scans are shown that pinpoint a second location **1020** of the aerial threat **120**. With this location information, the sector processor **910** can derive relative position information that can be used to provide divert commands to the eject vehicle **400** to more closely intercept the aerial threat **120**.

FIG. **11** is a spectrum diagram illustrating possible Doppler spectrum regions where various aerial vehicles may be detected. As non-limiting examples, FIG. **11** illustrates a ground clutter spectrum **1110**, a spectrum **1120** for the eject vehicle **400** (i.e., PRJ in FIG. **11**), a spectrum **1130** that may be indicative of an RPG, and a spectrum **1140** that may be indicative of a MANPAD. Of course, other aerial threats and their associated spectrums may also be identified.

FIG. **12** is a simplified flow diagram illustrating some of the processes **1200** involved in one or more embodiments of the present disclosure. The processes may be loosely considered as an acquisition phase **1210**, a pre-launch phase **1220**, an align and launch phase **1240**, a guidance phase **1260**, a divert phase **1270**, and a detonation phase **1280**.

Operation block **1212** indicates that continuous radar scans are performed looking for incoming aerial threats. Decision block **1214** indicates that the process loops until a target is detected. While not shown, during this phase the radar modules **900** may also be detecting distance and angle to wingman platforms (i.e., other aerial platforms) in the vicinity. Using communication between the various wingman platforms, sectors of responsibility can be identified as discussed more fully below in connection with FIG. **14**.

If a target is detected, the process **1200** enters the pre-launch phase **1220**. Operation block **1222** indicates that the sector processor **910** uses the range and travel direction of the incoming aerial threat **120** to calculate a threat direction to the incoming aerial threat **120** and an intercept vector pointing from a deployed eject vehicle **400** to a projected intercept point where the eject vehicle **400** would intercept the incoming aerial threat **120**. Operation block **1224** indicates that the intercept vector is sent to the eject vehicle **400**. The intercept vector may be sent to the eject vehicle **400** in a number of forms. The actual directional coordinates may be sent and the eject vehicle **400** would be responsible for determining the proper pitch maneuvers to perform. Alternatively, the sector processor **910** may determine the proper pitch maneuvers that the eject vehicle **400** should perform after launch and send only pitch commands (e.g., start and burn times for each alignment thruster **622**) to be used during the pitch maneuvers. While FIG. **12** indicates that the intercept vector or pitch commands are sent before launch, some embodiments may be configured such that this information can be sent after launch.

During the acquisition phase **1210** and pre-launch phase **1220**, the eject vehicle **400** remains in the dispenser **200** and connected to power. An RF communication link may be in operation through the eject vehicle **400** antenna via a transmission line inside the dispenser **200**.

The process enters the align and launch phase **1240** after the intercept vector is determined. Operation block **1242** indicates the impulse cartridge **750** is fired to propel the eject vehicle **400** from the dispenser **200** and safely away from the aerial platform **100**.

Operation block **1244** indicates that the pitch maneuvers are performed to align the eject vehicle **400** with the already determined intercept vector. The pitch maneuver is a two-stage process that sequentially executes an azimuth rotation and an elevation rotation to align the longitudinal axis of the eject vehicle **400** along the intercept vector. The pitch maneuver does not have to be exact. As a non-limiting example, offsets of up to about 10 to 15 degrees may be corrected during flight of the eject vehicle **400** using the divert thrusters **612** during the guidance phase **1260**. After ejection, the folding fins **482** will deploy and the communication link antennas **890** will deploy and wireless communication between the eject vehicle **400** and the radar module **900** may commence.

Operation block **1246** indicates that the rocket motor **420** will fire, which accelerates the eject vehicle **400** to about 160 meters/second and imposes a spin rate on the eject vehicle **400** of about 10 Hertz. Upon exhaustion, the rocket motor **420** and folding fins **482** will separate and the Terminal Vehicle (TV) is exposed. With separation of the TV, the second folding fins **484** deploy and the corner reflector **470** is exposed.

During the guidance phase **1260**, the process will perform a track and divert loop in order to adjust the flight path of the eject vehicle **400** to more closely intercept the aerial threat **120**. Operation block **1262** indicates that the sector processor **910** will track the eject vehicle **400** and aerial threat **120** as discussed above with reference to FIGS. **9A-10B**. Decision block **1264**, indicates that the sector processor **910** will determine if a divert maneuver is required to intercept the incoming aerial threat **120** and estimate the direction of divert thrust required.

A divert phase **1270** includes operations to cause the eject vehicle **400** to modify its course. Operation block **1272** indicates that the divert direction and time, if required, are sent to the eject vehicle **400**.

The divert process takes into account the rotation of the eject vehicle **400** and the direction of the desired divert thrust. This rotation adds a complication to the selection and fire time determination of the proper divert thruster **612**, but also ensures that all of the available divert thrusters **612** can be used to divert the eject vehicle **400** in any desired direction substantially perpendicular to the travel direction of the eject vehicle **400**. Operation block **1274** indicates that the processor on the eject vehicle **400** will select the divert thruster **612** to be fired and determine the firing time based on the divert angle received from the sector processor **910** and its internal attitude sensors.

Operation block **1276** indicates that the appropriate divert thruster **612** is fired at the appropriate fire time to move the eject vehicle **400** laterally along a diversion vector to adjust the flight path of the eject vehicle **400**. As a non-limiting example, each divert thruster **612** may be capable of correcting for about two degrees of error from the initial pointing of the eject vehicle **400** during the pitch maneuver. Thus, when the divert thrusters **612** are fired when the eject vehicle **400** is in the correct rotational position, the process can slide the travel direction vector of the eject vehicle **400** toward the path of the aerial threat **120**. Moreover, the process can fire in any circular direction and can fire multiple divert thrusters **612** in the same direction to repeatedly move the eject vehicle **400** in the same direction.

While FIG. **12** indicates the guidance phase **1260** and the detonation phase **1280** as operating sequentially, they also may operate in parallel. During the detonation phase **1280**, operation block **1282** indicates that the sector processor **910** determines an optimum intercept time when the eject vehicle **400** will be at its closest point to the aerial threat **120**. Operation block **1284** indicates that a detonation command may be sent to the eject vehicle **400**. This detonation command may be in the form of a detonation time for the eject vehicle **400** to count out or it may be in the form of an immediate command for the eject vehicle **400** to perform as soon as the command is received.

Operation block **1286** indicates that the warhead **440** on the eject vehicle **400** is detonated at the intercept time responsive to the detonation command received from the sector processor **910**.

FIG. **13** illustrates an example flight path for the eject vehicle **400** and an aerial threat **120** during an intercept process. In this example, a typical RPG and EV trajectory example are shown. The RPG is launched at a range of about 100 meters and 30 degrees left of the nose of the helicopter. The eject vehicle **400** receives its coordinate commands from the radar module **900** and is then ejected from the port chaff dispenser **200** at an angle of 90 degrees to the helicopter axis.

During period **1310**, the eject vehicle **400** separates to a distance of about two meters from the helicopter. During period **1320**, the nose thrusters **622** pitch the eject vehicle **400** to the approximate approach angle of the incoming RPG (e.g., within about ±10° accuracy). The rocket motor **420** then fires to accelerate the eject vehicle **400** to approximately 160 meters/second and is then separated from the remaining terminal vehicle upon exhaustion.

During period **1330**, the radar module **900** transmits a series of divert commands to the eject vehicle **400**, which fires the divert thrusters **612** to correct the trajectory of the eject vehicle **400** and intercept the RPG. A radar command is finally sent to the eject vehicle **400** to detonate the warhead **440** when the terminal vehicle reaches the closest point of approach (CPA). The guidance algorithm may be configured to produce a maximum CPA of about 30 centimeters, which is well within the lethal 0.6-meter kill radius of the warhead **440**.

FIG. **14** illustrates two aerial vehicles flying in a formation and various radar sectors that may be covered by the aerial vehicles. A significant concern is the presence of wingman helicopters and the potential damage caused by accidental targeting. The system presented has the capability of tracking and recognizing the adjacent helicopters and networking with their associated active protection systems to avoid collateral damage by handing off sectors covered by other platforms. In FIG. **14**, a first helicopter **1410** is monitoring a first radar sector **1410**A, a second radar sector **1410**B, a third radar sector **1410**C, and a fourth radar sector **1410**D.

A second helicopter **1420** near the first helicopter **1410** is monitoring a fifth radar sector **1420**A, a sixth radar sector **1420**B, a seventh radar sector **1420**C, and an eighth radar sector **1420**D. If an aerial threat approaches from a direction indicated by arrow **1430** it may be detected by the third radar sector **1410**C of the first helicopter **1410** and the seventh radar sector **1420**C of the second helicopter **1420**. If the first helicopter **1410** attempts to launch an eject vehicle, it may cause damage to the second helicopter **1420**. However, using communication between the various wingman platforms, sectors of responsibility can be identified. Thus, for the direction indicated by arrow **1430**, the first helicopter **1410** can determine that the third radar sector **1410**C will be covered by the seventh radar sector **1420**C of the second helicopter **1420**. As a result, while this formation continues, the first helicopter **1410** does not respond to threats in its third radar sector **1410**C.

Returning to FIG. **9**B, the radar module **900** may also be referred to herein more generically as an Engagement Management Module (EMM) **900**. As discussed above, in some embodiments, an aerial platform **100** (FIGS. **1**A and **1**B) may be configured with four engagement management modules **900**, an example of which is shown in FIG. **3**.

The engagement management modules **900** may be used as part of a Helicopter Active Protection System (HAPS), but may also be used in other types of aerial vehicles, ground vehicles, water vehicles, and stationary deployments.

Returning to FIGS. **4** through **5**C, the eject vehicle **400** may also be referred to herein as an intercept vehicle **400** and a kill vehicle (KV) **400**. FIG. **5**C illustrates the eject vehicle **400** after the rocket motor **420** has burned and been detached from the airframe shell **430**. At this stage, the eject vehicle **400** may be referred to as a terminal vehicle, a terminal section, or a terminal section of the kill vehicle **400**. Still within the terminal section are the warhead **440**, the divert thruster module **610**, the alignment thruster module **620**, the electronics module **450** the battery **452**, and the safe and arm module **460**.

In operation, radar on the EMM **900** detects and tracks an aerial threat (e.g., an RPG) launched at the helicopter and launches one or more KVs **400** from the AN/ALE-47 Countermeasure Dispenser to intercept the incoming RPG. Following launch, the KV **400** executes a series of pitch maneuvers using nose thrusters (i.e., in the alignment thruster module **620**) to align the body axis with the estimated intercept point, uses a boost motor to accelerate to high speed to intercept the RPG at maximum range, and executes a series of commands for lateral guidance maneuvers using a set of divert thrusters **610**. Finally, the KV **400** warhead **440** is command detonated when the KV **400** reaches the closest point of approach (CPA) computed by an EMM guidance processor.

The flight time of the KV is typically on the order of 300 to 500 msec. During the short flight time, the KV is exposed to strong moments due to divert thruster offsets from the center of gravity and to strong aerodynamic moments due principally to the Jet Interaction (JI) effect when the divert thrusters are fired. The principle forces of interest are shown in FIG. **15**.

FIG. **15** is a simplified side view of a kill vehicle (KV) **400** illustrating the principle forces of interest on the kill vehicle (KV) **400**. Ideally, the divert thruster's **610** center of thrust, $X_{CT}$, would be aligned with the KV **400** center of gravity (CG) to minimize any moments introduced by its thrust force ($F_{DT}$). However, even with balancing during manufacturing, there will be some migration of the CG as divert thrusters **610** and alignment thrusters **622** (FIGS. **6**A and **6**B and also referred to herein as "pitch thrusters **622**") and "attitude control thrusters **1604**" (FIG. **16**A) are fired and propellant is expended. Also, when the divert thrusters **610** are fired, airflow along a body **1510** of the KV **400** is disrupted, known as the Jet Interaction (JI) effect, which introduces a high pressure region **1506** in front of the divert thrusters **610** and a low pressure region **1508** aft of the divert thrusters **610**. This causes a moment that can be represented as a force $F_{JI}$ at location $X_{JI}$. The other principle aerodynamic component is the normal force $F_N$ introduced as a function of the angle of attack α, which is the angle between a body longitudinal axis **1520** and the velocity vector V. The normal force $F_N$ acts at the center of pressure $X_{CP}$.

One or more tail fins **1524** can be used to add aerodynamic stability, but the time constants associated with these tail fins generally are not fast enough to stabilize the KV **400** during its short flight time. Instead, or in addition to the tail fins **1524**, a plurality of small micro-thrusters **1604** (FIG. **16**A) are added to the nose thruster module **620** (FIGS. **4** and **16**A) to implement an active attitude control. This introduces $F_\mu$ at location $X_\mu$.

FIGS. **16**A and **16**B illustrate a nose thruster module **620**. The nose thruster module **620** may include a plurality of pitch thrusters **622** and a plurality of attitude control thrusters **1604**. FIG. **16**A illustrates a plurality of cylinders **1606** and **1608** configured for storing propellant grains. The larger cylinders **1606** correspond to the pitch thrusters **622** while the smaller cylinders **1608** correspond to the attitude control thrusters **1604**. FIG. **16**B illustrates a plurality of nozzles **1610** and **1612**, each configured to divert a flow from one of the plurality of cylinders **1606**, **1608**. Thus, the combination of cylinders **1606** and nozzles **1610** create the pitch thrusters **622** and the combination of cylinders **1608** and nozzles **1612** create the attitude control thrusters **1604**.

Referring again to FIG. **15**, The various moments described earlier may cause the KV **400** to become unstable and likely to tumble without stabilization. Maintaining the angle of attack α within a nominal 10 to 20 degrees is useful to maintain the divert thrusters **612** normal to the velocity vector V for proper guidance maneuvering and in directing the warhead **440** blast toward the RPG at the point of detonation.

FIG. **17** is a simplified block diagram of an attitude control loop **1700**. The EMM **900** radar generates position $\hat{d}_{KV}$ and velocity $\hat{v}_{KV}$ track data for the KV **400** and sends this information to the KV **400** via a command link radio (CLR) **1706**. The EMM **900** radar also transmits a roll angle $\hat{\phi}_{TX}$ via a transmit antenna **1804** (FIG. **18**) to the CLR **1706** to the KV **400** over the CLR **1706**. A Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) algorithm **1710**, resident in the KV **400**, processes the polarized CLR **1706** signal received by two orthogonal linear receive antennas **1802** (FIG. **18**) on the KV **400** to estimate a roll angle $\hat{\phi}_{KV}$ of the KV **400**. An onboard Inertial Management Unit (IMU) **1714** measures an acceleration a, and an angular velocity $\omega_{KV}$ of the KV **400**. This information is processed by an Extended Kalman Filter (EKF) **1720** to generate fused estimates of the position $\tilde{d}_{KV}$, velocity $\tilde{v}_{KV}$, attitude [$\tilde{\phi}_{KV}$, $\tilde{\theta}_{KV}$, $\tilde{\psi}_{KV}$], and angular velocity $\tilde{\omega}_{KV}$ of the KV **400**.

The Attitude Control Algorithm **1730** is designed to fire the nose mounted attitude control thrusters **1604** to maintain the angle of attack α (FIG. **15**) within preset limits. Once it is determined that an attitude correction thrust is required, the Attitude Control Algorithm **1730** selects the next available attitude control thruster **1604** that comes into position due to the body spin at operational block **1732**, and times the firing to coincide with the desired direction of thrust at operational block **1734**. The Attitude Control Algorithm **1730** maintains knowledge of which attitude control thrusters **1604** have been fired and which are available at operational block **1736**.

The KV **400** has an onboard IMU **1714** that measures the angular rate and acceleration. The IMU **1714** may include a set of 3-axis gyros, 3-axis accelerometers, 3-axis magnetometers, and a Field Programmable Gate Array (FPGA) to partially process the sensor information. The sensors may be solid-state MEMS that are machined on a small circuit board. The IMU **1714** also includes an FPGA that contains the EKF **1720** to fuse the output of the sensors into 3-dimensional position, velocity, angular velocity and attitude.

FIG. **18** is a simplified flowchart of the Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) algorithm **1710**. The JAPRAE algorithm **1710** may process the CLR **1706** signals received, for example, by orthogonal linearly polarized receive antennas **1802**, to adapt the two receive signals in a beam former **1806** (also referred to herein as "the dual polarized receiver **1806**") to match the incoming polarization to eliminate polarization mismatch loss induced by body rotation. The JAPRAE algorithm **1710** also processes the CLR **1706** signals received to provide an estimate of the KV **400** roll angle $\hat{\phi}_{rx}$.

The electric vector field of a propagating signal can be represented by a pair of orthogonal components:

$$E_{tx}(t) = [u_{tx\phi1}, u_{tx\phi2}]\begin{bmatrix} p_1(t) \\ p_2(t) \end{bmatrix} E_{tx} e^{i\omega_o t} = U_{tx} p E_{tx} e^{i\omega_o t} \quad (1)$$

where $u_{tx\phi1}$ and $u_{tx\phi2}$ are orthogonal unit vectors that define the direction of the electric field components, $p_1$ (t) and $p_2$ (t) are the complex components of a unit vector that define the projection of the electric field vector on the basis vectors, and U and p are the matrix of basis unit vectors and the polarization vector, respectively. Similarly, the polarization of an antenna can be defined by a 2×1 complex vector q. The signal received by an antenna with polarization q from a signal with polarization p is simply the inner product of p and q:

$$x_{rx}(t)=q(t)^H p(t)E(t)e^{i\beta(t)} \quad (2)$$

If polarizations p and q are defined in different coordinate systems, $U_{tx}$ and $U_{rx}$, then (2) becomes:

$$x_{rx}(t)=q(t)^H U_{rx}^T U_{tx} p(t)E(t)e^{i\beta(t)} \quad (3)$$

Assume the polarization of a source antenna **1804** and the receive antennas **1802** can be represented as $p_o$ and $q_o$ in terms of a natural antenna coordinate system. Let $A_{tx}(t)$ and $A_{rx}(t)$ be the time varying coordinate transformations from the natural coordinate system to some inertial system. In this system the electric field vector and receiver polarization vectors are given by:

$$E_{tx}(t)=A_{tx}(t)U_{tx}p_oE(t)e^{i\beta(t)}$$

$$q(t)=A_{rx}(t)U_{rx}q_o. \quad (4)$$

Then, becomes:

$$x_{rx}(t)=q_o^H u_{rx}^T A_{rx}^T(t)A_{tx}(t)U_{tx}p_oE(t)e^{i\beta(t)} \quad (3)$$

In the JAPRAE system **1710** there are two orthogonal receive antennas **1802**, with polarizations $q_{o1}$ and $q_{o2}$. Thus, the signal generated at the input of the dual polarized receiver **1806** is given by:

$$x_{rx}(t)=\begin{bmatrix} x_{rx1}(t) \\ x_{rx2}(t) \end{bmatrix}=\begin{bmatrix} q_{o1}^H U_{rx}^T A_{rx}^T(\phi_{rx})A_{tx}(\phi_{tx})U_{tx}p_o \\ q_{o2}^H U_{rx}^T A_{rx}^T(\phi_{rx})A_{tx}(\phi_{tx})U_{tx}p_o \end{bmatrix}E(t)e^{i\beta(t)} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}E(t)e^{i\beta(t)} = aE(t)e^{i\beta(t)} \quad (4)$$

In equation (4) the transformations are explicitly represented as rotations of the transmitter $\phi_{tx}$ and receiver $\phi_{rx}$ around the line of sight. In the case where the transmit antenna **1804** and the receive antennas **1802** are linearly polarized, it can be shown that this reduces to the following form:

$$x_{rx}(t)=\begin{bmatrix} \cos(\phi_{tx}-\phi_{rx}) \\ -\sin(\phi_{tx}-\phi_{rx}) \end{bmatrix}E(t)e^{i\beta(t)}=\begin{bmatrix} \cos(\delta) \\ -\sin(\delta) \end{bmatrix}E(t)e^{i\beta(t)} \quad (5)$$

Consider a signal y(t) generated by performing a rotation on the vector x(t).

$$y_{rx}(t)=\begin{bmatrix} y_{rx1}(t) \\ y_{rx2}(t) \end{bmatrix}=\begin{bmatrix} \cos(\hat{\delta}) & -\sin(\hat{\delta}) \\ \sin(\hat{\delta}) & \cos(\hat{\delta}) \end{bmatrix}\begin{bmatrix} \cos(\delta) \\ -\sin(\delta) \end{bmatrix}E(t)e^{i\beta(t)} = \begin{bmatrix} \cos(\hat{\delta})\cos(\delta)+\sin(\hat{\delta})\sin(\delta) \\ \sin(\hat{\delta})\cos(\delta)-\cos(\hat{\delta})\sin(\delta) \end{bmatrix}E(t)e^{i\beta(t)} = \begin{bmatrix} \cos(\hat{\delta}-\delta) \\ \sin(\hat{\delta}-\delta) \end{bmatrix}E(t)e^{i\beta(t)} \quad (8)$$

Note that if $\hat{\delta}=\delta$, $y_{rx1}=Ee^{i\beta(t)}$ and $y_{rx0}=\mathbf{0}$. This amounts to a case where $y_{rX1}$ is the output of a beamformer that matches the polarization of the incident signal to maximize the receive signal power. It can be shown that this also maximizes the signal-to-noise ratio.

Now form the ratio of y2(k) to y1(k)

$$r(t)=\frac{y_{rx2}(t)}{y_{rx1}(t)}=\frac{\sin(\hat{\delta}-\delta)E(t)e^{i\beta(t)}}{\cos(\hat{\delta}-\delta)E(t)e^{i\beta(t)}}=\tan(\hat{\delta}-\delta) = \tan(\hat{\delta}-\delta) \quad (9)$$

This forms the basis for generating an error signal for an adaptive polarization loop.

$$e_\delta(t)=\hat{\delta}(t)-\delta(t)=\tan^{-1}\left(\frac{y_2(t)}{y_1(t)}\right) \quad (10)$$

FIG. **19** illustrates the JAPRAE algorithm **1710** (FIG. **17**) in the form of a conventional servo loop **1900**. The closed loop may force $y_{rx2}$ to zero, hence $\hat{\delta}\rightarrow\delta$. Under closed loop conditions, the KV **400** roll angle is estimated by:

$$\hat{\theta}_{rx}(t)=\hat{\theta}_{tx}(t)-\hat{\delta}(t) \quad (6)$$

The transmitter roll angle, $\hat{\phi}_{tx}$, can be transmitted to the KV **400** via the data link **1806**.

FIG. **20** illustrates a non-limiting example of a set of simulation results **2000** of the JAPRAE algorithm **1710** (FIG. **17**) tracking the roll angle of a KV **400** body spinning on its longitudinal axis **1520** (FIG. **15**) at 2200 degrees per second. A top plot **2002** of FIG. **20** illustrates an overlay of true and estimated roll angles. A bottom plot **2004** illustrates a difference or error between the overlay of true and estimated roll angles. The set of simulation results **2000** are shown without additive noise and illustrate the performance of the servo loop **1900** (FIG. **19**).

Note that the solution for equation 10 is ambiguous by π radians. Therefore, the loop **1900** of FIG. **19** should be initialized near the correct angle to avoid the ambiguity.

A Kalman Filter methodology is used to fuse the sensor data. The translational motion involves a set of linear equations and the conventional Kalman Filter (KF) can be used, whereas the rotational motion involves a set of non-linear equations and the conventional Extended Kalman Filter (EKF) can be used.

A 9×1 discrete time translational motion state vector, x(k), includes 3-D spatial components comprising a position vector, d(k), a velocity vector, v(k), and an acceleration vector, a(k), as follows:

$$x(k)=[d^T(k),v^T(k),a^T(k)]^T \quad (12)$$

Transition and measurement equations include a transition matrix, $F_k$, a plant noise coupling matrix, $G_k$, a measurement matrix, $H_k$, state transition noise $w_k$ and measurement noise $v_k$.

$$x_{k+1}=FX_k+G_kw_k$$

$$z_k=H_kx_k+v_k \quad (13)$$

The state transition noise $w_k$ is i.i.d. zero mean Gaussian with covariance $R_k$, and the measurement noise $v_k$ is also i.i.d. zero mean Gaussian with covariance $Q_k$. The subscript k indicates the variables might be time varying.

The expanded form of these equations is given by:

$$\begin{bmatrix} d_{k+1} \\ v_{k+1} \\ a_{k+1} \end{bmatrix}=\begin{bmatrix} I_3 & T_sI_3 & 0.5T_s^2I_3 \\ 0_3 & I_3 & T_sI_3 \\ 0_3 & 0_3 & I_3 \end{bmatrix}\begin{bmatrix} d_k \\ v_k \\ a_k \end{bmatrix}+\begin{bmatrix} 0.5T_s^2I_3 \\ T_sI_3 \\ I_3 \end{bmatrix}\begin{bmatrix} w_{d,k} \\ w_{v,k} \\ w_{wa,k} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} z_{d,k} \\ z_{v,k} \\ z_{a,k} \end{bmatrix}=\begin{bmatrix} I_3 & 0_3 & 0_3 \\ 0_3 & I_3 & 0_3 \\ 0_3 & 0_3 & I_3 \end{bmatrix}\begin{bmatrix} d_k \\ v_k \\ a_k \end{bmatrix}+\begin{bmatrix} v_{d,k} \\ v_{v,k} \\ v_{a,k} \end{bmatrix}$$

where $T_s$ is the sample interval and $I_3$ and $0_3$ are 3×3 unity and zero matrices, respectively.

The Kalman filter **1720** (FIG. **17**) involves two acts: the projection act and the update act.

The projection act is given by:

$$\hat{x}_{k|k+1}=F_k\hat{x}_{k-1|k-1}$$

$$\hat{P}_{k|k+1}=F_k\hat{P}_{k-1|k-1}F_k^T+G_kQ_kG_k^T \quad (15)$$

The update act is given by:

$$L_k=\hat{P}_{k|k-1}H_k^T[H_k\hat{P}_{k|k-1}H_k^T+R_k]^{-1}$$

$$\hat{x}_{k|k}=F\hat{x}_{k|k-1}+L_k[z_k-H_k\hat{x}_{k|k-1}]$$

$$\hat{P}_{k|k}=\hat{P}_{k|k-1}-\hat{P}_{k|k-1}H_k^T[H_k\hat{P}_{k|k-1}H_k^T+R_k]^{-1}H_k^T\hat{P}_{k|k-1}^T \quad (16)$$

The 9×1 discrete time translational motion state vector, $\bar{x}(k)$ comprises 3-D spatial components including attitude, θ(k), and angle rate, ω(k). An overbar is used to distinguish the rotational variables from the translational variables:

$$\bar{x}(k)=[\theta^T(k),\omega^T(k)]^T \tag{17}$$

The transition and measurement equations have a similar form as the translational equations except the transition equation is nonlinear.

$$\bar{x}_{k+1}=\bar{F}_k(y_k)+\bar{G}_k\bar{w}_k$$

$$\bar{z}_{k+1}=\bar{H}_k y_k+\bar{v}_k \tag{18}$$

The transition noise, $\bar{w}_k$ is i.i.d. zero mean Gaussian with covariance $\bar{R}_k$ and the measurement noise $\bar{v}_k$ is i.i.d. Gaussian with covariance $\bar{Q}_k$. The nonlinear property is shown in the expanded form.

$$\begin{bmatrix} \bar{x}_{\theta,k+1} \\ \bar{x}_{\omega,k+1} \end{bmatrix} = \begin{bmatrix} I_3 & T_s B(\theta_k) \\ 0_3 & I_3 \end{bmatrix} \begin{bmatrix} \bar{x}_{\theta,k} \\ \bar{x}_{\omega,k} \end{bmatrix} + \begin{bmatrix} 0_3 \\ I_3 \end{bmatrix} \begin{bmatrix} \bar{w}_{\theta,k} \\ \bar{w}_{\omega,k} \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} \bar{z}_{\phi,k} \\ \bar{z}_{\omega,k} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ & 0_3 & & & I_3 & \end{bmatrix} \begin{bmatrix} \bar{x}_{\theta,k} \\ \bar{x}_{\omega,k} \end{bmatrix} + \begin{bmatrix} \bar{v}_{\theta,k} \\ \bar{v}_{\omega,k} \end{bmatrix}$$

The nonlinear matrix $B(\theta_k)$ converts angle rate to Euler angle rate and is given by:

$$B(\theta_k) = \begin{bmatrix} 1 & \sin(\phi)\tan(\theta) & \cos(\phi)\tan(\theta) \\ 0 & \cos(\phi) & -\sin(\phi) \\ 0 & \sin(\phi)\sec(\theta) & \cos(\phi)\sec(\theta) \end{bmatrix} \tag{20}$$

The EKF method is similar to the KF method except the transition equation is linearized using the Jacobian.

$$\bar{F}_k = \frac{\partial \bar{F}_k(y_k)}{\partial \bar{x}_k} = \left[ \frac{\partial \bar{F}_k(y_k)}{\partial \theta} \; \frac{\partial \bar{F}_k(y_k)}{\partial \omega} \right] \tag{21}$$

The two derivatives are:

$$\frac{\partial \bar{F}_k(y_k)}{\partial \theta} = \begin{bmatrix} 1 + T_s(\cos(\phi)\tan(\theta)\omega_{y,k} - \sin(\phi)\tan(\theta)\omega_{z,k}) & T_s(\sin(\phi)\sec^2(\theta)\omega_{y,k} + \cos(\phi)\sec^2(\theta)\omega_{z,k}) & 0 \\ -T_s\sin(\phi)\omega_{y,k} - T_s\cos(\phi)\omega_{z,k} & 1 & 0 \\ T_s(\cos(\phi)\sec(\theta)\omega_{y,k} - \sin(\phi)\sec(\theta)\omega_{z,k}) & T_s(\sin(\phi)\sec(\theta)\tan(\theta)\omega_{y,k} + \cos(\phi)\sec(\theta)\tan(\theta)\omega_{zk}) & 1 \end{bmatrix}$$

$$\frac{\partial \bar{F}_k(y_k)}{\partial \omega} = T_s B(\theta_k)$$

From this point on, the EKF method is similar to the KV method using the linearized components.

The projection step for the EKF is given by:

$$\bar{\hat{x}}_{k|k+1}=F_k\bar{\hat{x}}_{k-1|k-1}$$

$$\bar{\hat{P}}_{k|k+1}=F_k\bar{\hat{P}}_{k-1|k-1}F_k^T+G_kQ_kG_k^T \tag{22}$$

The update step for the EKF is given by:

$$L_k=\bar{P}_{k|k-1}H_k^T[H_k\bar{P}_{k|k-1}H_k^T+R_k]^{-1}$$

$$\bar{\hat{x}}_{k|k}=F\bar{\hat{x}}_{k|k-1}+L_k[z_k-H_k\bar{\hat{x}}_{k|k-1}]$$

$$\bar{\hat{P}}_{k|k}=\bar{\hat{P}}_{k|k-1}-\bar{\hat{P}}_{k|k-1}H_k^T[H_k\bar{\hat{P}}_{k|k-1}H_k^T+R_k]^{-1}H_k^T\bar{\hat{P}}_{k|k-1}^T \tag{23}$$

FIGS. **21**, **22**, and **23** illustrate sets of simulation results of the EKF fusion algorithm using the EMM **900** radar, JAPRAE **1710** and IMU **1714** (FIG. **17**) inputs for a typical KV **400** flight profile. FIG. **21** illustrates position results of the simulation. A top plot illustrates true position values, a middle plot illustrates estimated position values, and a bottom plot illustrates position error. An x position is indicated by solid lines or blue lines, a y position is indicated by dotted lines or green lines, and a z position is indicated by dashed lines or red lines.

FIG. **22** illustrates velocity results of the simulation. A top plot illustrates true velocity values, a middle plot illustrates estimated velocity values, and a bottom plot illustrates velocity error. An x velocity is indicated by solid lines or blue lines, a y velocity is indicated by dotted lines or green lines, and a z velocity is indicated by dashed lines or red lines.

FIG. **23** illustrates attitude results of the simulation. A top plot illustrates true attitude values, a middle plot illustrates estimated attitude values, and a bottom plot illustrates attitude error. An x attitude is indicated by solid lines or blue lines, a y attitude is indicated by dotted lines or green lines, and a z attitude is indicated by dashed lines or red lines.

FIG. **24** illustrates an attitude control loop **2400**. The attitude control loop **2400** utilizes an uplink and onboard EKF outputs to compute firing commands to the plurality of Attitude Control Thrusters (ACT) **1604** to maintain the KV **400** body axis **1520** aligned with the velocity vector V (FIG. **15**).

In FIG. **24**, $\tilde{d}_{KV}$ and $\tilde{v}_{KV}$ are projectile position and velocity vectors in the North-East-Down (NED) frame. $[\tilde{\phi}_{KV}, \tilde{\theta}_{KV}, \tilde{\psi}_{KV}]$ are body Euler angles and $\tilde{\omega}_{KV}$ is body rate vector. The projectile mass, CG location and inertia tensor are updated whenever there is a divert thruster **610** or an attitude thruster **1604** firing. The attitude control loop **2400** may include an Attitude Control Algorithm **2402**. The Attitude Control Algorithm **2402** may compute how much attitude control thrust is needed at the attitude thruster station **620** and which direction the thrust centroid should point to. If the Attitude Control Thrust (ACT) exceeds a certain fraction of the ACT force, then the algorithm may initiate a command to fire an ACT. The Attitude Thruster Select function then searches for an ACT to fire at operational block **2404**. If the selected ACT is at the desired ignition position, the Attitude Thruster Fire Control electronics squib the selected ACT to fire at operational block **2406**. Otherwise, the process exits the control loop. Finally, the Attitude Thruster Units Remaining function **2410** keeps track of which ACTs are spent and which are available for use. This information is fed back to the Mass Property Estimator function **2412** and the Attitude Thruster Select function **2404**.

Operation may be as explained in acts 1 through 12 below:

Act 1: The onboard EKF algorithm tracks the projectile yaw ($\tilde{\psi}_{KV}$), pitch ($\tilde{\theta}_{KV}$) and roll ($\tilde{\omega}_{KV}$) attitude angles. These angles are used to compute the NED to body directional cosine matrix $C_n^b$ as

$$C_n^b=\begin{bmatrix}1&0&0\\0&\cos\tilde{\phi}_{KV}&\sin\tilde{\phi}_{KV}\\0&-\sin\tilde{\phi}_{KV}&\cos\tilde{\phi}_{KV}\end{bmatrix}\cdot\begin{bmatrix}\cos\tilde{\theta}_{KV}&0&-\sin\tilde{\theta}_{KV}\\0&1&0\\\sin\tilde{\theta}_{KV}&0&\cos\tilde{\theta}_{KV}\end{bmatrix}\cdot\begin{bmatrix}\cos\tilde{\psi}_{KV}&\sin\tilde{\psi}_{KV}&0\\-\sin\tilde{\psi}_{KV}&\cos\tilde{\psi}_{KV}&0\\0&0&1\end{bmatrix}\quad(24)$$

Act 2: The projectile velocity in the NED frame, $\tilde{V}_{KV}$, is tracked by EMM **900** radar and uplinked to the projectile via RF communication links. The velocity is then transformed into the body frame.

$$\tilde{V}_{KV}^{\ b}=C_n^{\ b}\cdot\tilde{V}_{KV}\quad(25)$$

Act 3: The total angle of attack $\alpha_{total}$ and aerodynamic roll angles $\phi_{aero}$ is then computed. The total angle of attack should be small at all times. The aerodynamic angle tells where the total angle of attack is relative to the body roll axis.

$$\alpha_{total}=\tan^{-1}\left(\frac{\sqrt{\tilde{V}_{KV}^{b}(2)^2+\tilde{V}_{KV}^{b}(3)^2}}{\tilde{V}_{KV}^{b}(1)}\right)\quad(26)$$

$$\varphi_{aero}=\tan^{-1}\left(\frac{\tilde{V}_{KV}^{b}(2)}{\tilde{V}_{KV}^{b}(3)}\right)$$

Act 4: The attitude changing rate cannot be measured for the purpose of rate feedback, but the synthetic rates may be derived by using the relationship between the attitude rate and the estimated body rates and attitude angles as

$$\dot{\psi}_{KV}=(\tilde{\omega}_{KV}(2)\sin\tilde{\phi}_{KV}+\tilde{\omega}_{KV}(3)\cos\tilde{\phi}_{KV})sec\tilde{\theta}_{KV}$$

$$\dot{\theta}_{KV}=\tilde{\omega}_{KV}(2)\cos\tilde{\phi}_{KV}-\tilde{\omega}_{KV}(3)\sin\tilde{\phi}_{KV}$$

$$\dot{\phi}_{KV}=\tilde{\omega}_{KV}(1)+\dot{\psi}_{KV}\sin\tilde{\theta}_{KV}\quad(27)$$

Act 5: Compute the KV **400** heading and flight path angles in the NED frame. These are the desired body yaw and pitch attitude angles that we want to control. Note that the body roll angle is free.

$$\psi_{cmd}=\tan^{-1}\left(\frac{\tilde{V}_{KV}(2)}{\tilde{V}_{KV}(1)}\right)\quad(28)$$

$$\theta_{cmd}=\tan^{-1}\left(\frac{-\tilde{V}_{KV}(3)}{\sqrt{\tilde{V}_{KV}(1)^2+\tilde{V}_{KV}(2)^2}}\right)$$

Act 6: Compute attitude error by subtracting the estimated attitude angles from the commanded attitude angles above. This error is then multiplied by a proportional gain $K_{p,outer}$ to form attitude angle rate command.

$$\dot{\psi}_{cmd}=K_{p,outer}(\psi_{cmd}-\tilde{\psi}_{KV})$$

$$\dot{\theta}_{cmd}=K_{p,outer}(\theta_{cmd}-\tilde{\theta}_{KV})\quad(29)$$

Act 7: Compute attitude rate errors by subtracting the attitude rate derived in Act 4 above from the rate commands above. These rate errors are multiplied by a proportional gain $K_{p,inner}$ to form attitude acceleration commands.

$$\ddot{\psi}_{cmd}=K_{p,inner}(\dot{\psi}_{cmd}-\dot{\psi}_{KV})$$

$$\ddot{\theta}_{cmd}=K_{p,inner}(\dot{\theta}_{cmd}-\dot{\theta}_{KV})\quad(9)$$

FIG. **25** illustrates a controller input-output topology. The yaw and pitch commands are derived from Act 5. The estimated body attitude angles, Euler, and body rates, ω, are provided by the JAPRAE algorithm **1710**. The controller gain $Kp_{outer}$ and $Kp_{inner}$ are to be optimized for various engagement scenarios. The symbol $Euler_d$ represents the Euler rate vector $[\dot{\psi}_{KV}, \dot{\theta}_{KV}, \dot{\phi}_{KV}]$. $Euler_{dd}$ represents the Euler acceleration vector $[\ddot{\psi}_{KV}, \ddot{\theta}_{KV}, \ddot{\phi}_{KV}]$. And, $F_{cmd}$ is the output of the controller containing the magnitude of the attitude thrust force command and its orientation relative to the body roll axis **1520**. The function that computes the force command is described in Acts 8 through 10.

Act 8: Because the air vehicle is aerodynamically unstable at all flight regimes, angle of attack will grow if unchecked. For this reason, the aerodynamic moment to be countered must be estimated, in addition to the moment needed to produce the attitude acceleration of Act 7. The estimation is done by storing a complete set of aerodynamic coefficient tables on board the projectile and computing the total yawing and pitching moments about the estimated CG location on the flight. The algorithm to estimate the KV **400** mass, CG location and inertia tensor will be described below with respect to FIG. **27**. The total aerodynamic moment in the body frame, ignoring the rolling moment, may be computed as:

$$M^b=Qsd\begin{Bmatrix}0\\C_m\\C_n\end{Bmatrix}\quad(31)$$

$$C_m=(\overline{X}_{CP}-\overline{X}_{CG})*C_N+C_{m_q}\overline{q}+C_A\overline{Z}_{CG}$$

$$C_n=(\overline{X}_{CP}-\overline{X}_{CG})*C_Y+C_{n_r}\overline{r}-C_A\overline{Y}_{CG}$$

Where:

Q is dynamic pressure

S is reference area

d is reference diameter

$C_m$ is total pitching moment coefficient

$C_n$ is total yawing moment coefficient)

$\overline{X}_{CP}$ is normalized center of pressure location along the body x-axis

$\overline{X}_{CG}$ is normalized center of gravity location along the body x-axis

$\overline{Y}_{CG}$ is CG offset from the body x-axis

$\overline{Z}_{CG}$ is CG offset from the body x-axis

$C_A$ is axial drag-force coefficient

$C_N$ is normal force coefficient

$C_y$ is lateral force coefficient

$C_{m_q}$ is pitch damping coefficient

$C_{n_r}$ yaw damping coefficient

$\overline{q}$ is normalized pitching rate

$\overline{r}$ is normalized yawing rate.

Act 9: The instantaneous moment about the CG location required to produce the attitude acceleration which will force the body to align with the velocity vector V (FIG. **15**) can now be calculated as:

$$M_{cmd}=-\begin{bmatrix}0&0&0\\0&-\sin\tilde{\phi}_{KV}&-\cos\tilde{\phi}_{KV}\\0&-\cos\tilde{\phi}_{KV}&\sin\tilde{\phi}_{KV}\end{bmatrix}\begin{Bmatrix}0\\c_2\\c_3\end{Bmatrix}I_t.\quad(32)$$

$I_t$ is the estimated moment of inertia about the lateral axis and $c_2$ and $c_3$ are computed as:

$$c_2=\cos\tilde{\theta}_{KV}\ddot{\psi}_{cmd}-\sin\tilde{\theta}_{KV}\dot{\theta}_{KV}\dot{\psi}_{KV}-(\tilde{\omega}_{KV}(2)\cos\tilde{\phi}_{KV}-\tilde{\omega}_{KV}(3)\sin\tilde{\phi}_{KV})\dot{\psi}_{KV}-(I_t-I_a)(\tilde{\omega}_{KV}(1)\tilde{\omega}_{KV}(3)\sin\tilde{\phi}_{KV}+\tilde{\omega}_{KV}(1)\tilde{\omega}_{KV}(2)\cos\tilde{\phi}_{KV}$$

$$c_3=\ddot{\theta}_{cmd}+(\tilde{\omega}_{KV}(2)\sin\tilde{\phi}_{KV}+\tilde{\omega}_{KV}(3)\cos\tilde{\omega}_{KV})\dot{\phi}_{KV}-(I_t-I_a)(\tilde{\omega}_{KV}(1)\tilde{\omega}_{KV}(3)\cos\tilde{\phi}_{KV}-\tilde{\omega}_{KV}(1)\tilde{\omega}_{KV}(2)\sin\tilde{\phi}_{KV} \quad (33)$$

$I_a$ denotes the estimated moment of inertia about the roll axis.

Act 10: Given the estimated CG location, $X_{CG}$, and the attitude nozzle location, $X_{AT}$, we can convert the above moment command to thrust force command as:

$$F_{cmd}=\begin{Bmatrix} 0 \\ M_{cmd}(3)-M^b(3) \\ -M_{cmd}(2)+M^b(2) \end{Bmatrix}\frac{1}{X_{AT}-X_{CG}} \quad (34)$$

The magnitude of this command is:

$$F_{total}=\|F_{cmd}\| \quad (35)$$

And, the roll orientation relative to the body y-axis is:

$$\phi_{cmd}=\tan^{-1}\left(\frac{F_{cmd}(3)}{F_{cmd}(2)}\right) \quad (36)$$

Act 11: If the thrust force command, $F_{total}$, is greater than a threshold value, usually a fraction of the attitude thruster force, a thruster search algorithm may be initiated to find a thruster to fire. Otherwise, no attitude thruster may be fired.

FIG. **26** illustrates an example of a search procedure that may be used to find a thruster to fire. A plurality of attitude thrusters **1**, **2**, **3**, **4**, **5**, **6**, **7**, and **8** are shown with circles. A white circle, such as attitude thrusters **1**, **4**, **6**, and **8**, indicates the attitude thruster has been spent. A shaded circle, such as attitude thrusters **2**, **3**, **5**, and **7**, indicates the attitude thruster has not been spent.

From Act 3, a total angle of attack is found between the body x-axis and the velocity vector $V^b$ and the aerodynamic angle relative to the body z-axis. To reduce the total angle of attack, an attitude thruster may be fired 180 degrees opposite to $\phi_{aero}$ such that the resultant force F pushes the body nose toward the velocity vector. Knowing the duration of the attitude thruster burn and time delays from the thruster command generation to actual thruster ignition, may enable calculation of the proper roll angle to issue the attitude thruster squib command. If there happens to be an attitude thruster at the right place at the moment, that thruster will be selected to fire. For example, in FIG. **26**, attitude thruster number **8** is about to reach the ignition command position; but it has already been spent, so it can't be selected. Thruster number **7** is available but it's too soon to be fired so it will not be selected, either. However, as the KV **400** precesses and nutates, the ignition command angle $\phi_{ignit,cmd}$ and thruster number **7** may line up and be selected to fire.

Act 12: The attitude control loop may keep track of which attitude thrusters are available to use in an availability list. When a certain attitude thruster is commanded to fire, it is removed from the availability list.

Because of the high mass ratio of the divert thruster **610** and the attitude thruster **1604** propellants to the KV **400** total mass, the CG location and the inertia tensor will migrate as any divert thruster **610** or an attitude thruster **1604** is firing. This is the so-called CG migration problem and it becomes more important toward the end of flight when most of the thrusters are spent.



FIG. **27** illustrates a mass and CG location update algorithm **2700**. The mass and CG location update algorithm **2700** may be configured to update the total mass, CG location and inertia tensor as a divert thruster **610** or attitude thruster **1604** is firing. The definitions of the symbols are:

$\dot{m}_i \equiv i^{th}$ thruster mass burn rate<0

$r_i \equiv i_{th}$ thruster $CG$ location

$m \equiv$ total mass

$r_{CG} \equiv Cg$ location

$I_{xy} \equiv$ Inertia tensor element $xy$ (37)

The following equations are computed recursively:

$$\begin{aligned}
&\Delta m_i=\dot{m}_i\cdot dt<0 \quad (38)\\
&m(t_k)=m(t_{k-1})+\Delta m_i\\
&r_{CG}(t)=\frac{m(t_{k-1})r_{CG}(t_{k-1})+\Delta m_i r_i}{m(t_k)}\\
&I_{xx}(t_k)=I_{xx}(t_{k-1})-\sum\Delta m_i(y_i^2+z_i^2)\\
&I_{yy}(t_k)=I_{yy}(t_{k-1})-\sum\Delta m_i(x_i^2+z_i^2)\\
&I_{zz}(t_k)=I_{zz}(t_{k-1})-\sum\Delta m_i(x_i^2+y_i^2)\\
&I_{xy}(t_k)=I_{xy}(t_{k-1})+\sum\Delta m_i x_i y_i\\
&I_{xz}(t_k)=I_{xz}(t_{k-1})+\sum\Delta m_i x_i z_i\\
&I_{yz}(t_k)=I_{yz}(t_{k-1})+\sum\Delta m_i y_i z_i
\end{aligned}$$

To a large extent, this detailed description has focused on a particular type of intercept vehicle (e.g., the eject vehicle **400**). However, engagement management systems described herein may be used with many types of intercept vehicles **400** in which the engagement management system can track the intercept vehicle **400**, alter the course of the intercept vehicle **400**, determine when to detonate the intercept vehicle **400**, or combinations thereof using commands communicated between the engagement management system and the intercept vehicle **400**.

Moreover, while embodiments of the present disclosure may be particularly suitable for use on aerial platforms, they may also be used in other types of mobile platforms like ground-based mobile platforms such as, for example, tanks, armored personnel carriers, personnel carriers (e.g., Humvee and Stryker vehicles) and other mobile platforms capable of bearing embodiments of the present disclosure. Moreover, embodiments of the present disclosure may be used for relatively stationary ground-based personnel protection wherein a mobile platform may not be involved. Accordingly, embodiments of the disclosure are not limited to aerial applications.

While the present disclosure has been described herein with respect to certain illustrated embodiments, those of ordinary skill in the art will recognize and appreciate that the present invention is not so limited. Rather, many additions, deletions, and modifications to the illustrated and described embodiments may be made without departing from the scope of the invention as hereinafter claimed along with their legal equivalents. In addition, features from one embodiment may be combined with features of another embodiment while still being encompassed within the scope of the invention as contemplated by the inventor.

What is claimed is:

1. An eject vehicle for disposition in and ejection from a dispenser, the eject vehicle comprising:

a plurality of pitch thrusters configured to perform a pitch maneuver to generate a perpendicular force on the eject vehicle relative to a longitudinal axis of the eject vehicle after ejection of the eject vehicle to rotate and substantially align the eject vehicle with an intercept vector pointed toward an interception point for an identified aerial threat;

a rocket motor configured to perform a thrust maneuver to accelerate the eject vehicle along the longitudinal axis of the eject vehicle;

one or more divert thrusters configured to perform a divert maneuver on the eject vehicle in a direction substantially perpendicular to the intercept vector; and

two orthogonal linearly polarized receive antennas, outputs thereof being adaptively combined to match incoming polarization of received signals to substantially eliminate polarization mismatch loss induced by body rotation of the eject vehicle.

2. The eject vehicle of claim 1, wherein the one or more divert thrusters are further configured to compensate for an expected high pressure region forward of the divert thrusters and an expected low pressure region aft of the divert thrusters.

3. The eject vehicle of claim 1, further comprising a plurality of attitude control thrusters positioned forward or aft of the eject vehicle center of gravity and configured to make adjustments to an attitude of the eject vehicle when activated.

4. The eject vehicle of claim 3, further comprising an electronics module configured for performing an attitude control algorithm to use a determination of an angle of attack of the eject vehicle to determine an appropriate time to fire an attitude control thruster of the plurality of attitude control thrusters to adjust the attitude of the eject vehicle to a desired orientation.

5. The eject vehicle of claim 1, further comprising an inertial management unit configured to determine at least one of acceleration, velocity, and position information in at least an angular coordinate of the eject vehicle responsive to one or more sensors selected from the group consisting of accelerometers, gyros, and magnetometers.

6. The eject vehicle of claim 5, further comprising an electronics module for performing a Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) configured to determine a roll estimation by synthesizing information from the two orthogonal linearly polarized receive antennas and information from the inertial management unit.

7. The eject vehicle of claim 6, wherein the JAPRAE is configured to determine the roll estimation using an extended Kalman filter.

8. The eject vehicle of claim 5, further comprising an electronics module for performing a Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) configured to adaptively combine the signals from the two orthogonal linearly polarized receive antennas to match the polarization of the incident signal.

9. The eject vehicle of claim 1, further comprising:

an impulse cartridge configured to fire responsive to a command from an aerial platform bearing the eject vehicle; and

an ejection piston configured to propel the eject vehicle away from the aerial platform responsive to the firing of the impulse cartridge.

10. The eject vehicle of claim 1, further comprising a warhead configured to detonate when the eject vehicle is away from the dispenser and within a predetermined range of the identified aerial threat.

11. A method of intercepting an aerial threat, comprising:

ejecting an eject vehicle from a dispenser;

performing a pitch maneuver with a plurality of pitch thrusters of the eject vehicle to align the eject vehicle along an intercept vector pointed substantially toward a projected intercept point with an identified aerial threat;

performing a thrust maneuver with a rocket motor of the eject vehicle to accelerate the eject vehicle;

performing a divert maneuver with one or more divert thrusters of the eject vehicle to divert the eject vehicle from the intercept vector one or more times after commencement of accelerating the eject vehicle to adjust a course of the eject vehicle to align the eject vehicle along an updated intercept vector; and

processing received signals from two orthogonal linearly polarized receive antennas to match incoming polarization of the received signals to substantially eliminate polarization mismatch loss induced by body rotation of the eject vehicle.

12. The method of claim 11, further comprising compensating for an expected high pressure region forward of the divert thrusters and an expected low pressure region aft of the divert thrusters when diverting the eject vehicle.

13. The method of claim 11, further comprising making adjustments to an attitude of the eject vehicle with a plurality of attitude control thrusters positioned near a front or rear of the eject vehicle.

14. The method of claim 13, further comprising performing an attitude control algorithm using a determination of a roll estimation of the eject vehicle to determine an appropriate time to fire an attitude control thruster of the plurality of attitude control thrusters to adjust the attitude of the eject vehicle to a desired orientation.

15. The method of claim 11, further comprising determining at least one of acceleration, velocity, and position information in at least an angular coordinate of the eject vehicle with an inertial management unit.

16. A method of intercepting an aerial threat, comprising:

ejecting an eject vehicle from a dispenser;

performing a pitch maneuver with a plurality of pitch thrusters of the eject vehicle to align the eject vehicle along an intercept vector pointed substantially toward a projected intercept point with an identified aerial threat;

performing a thrust maneuver with a rocket motor of the eject vehicle to accelerate the eject vehicle;

performing a divert maneuver with one or more divert thrusters of the eject vehicle to divert the eject vehicle from the intercept vector one or more times after commencement of accelerating the eject vehicle to adjust a course of the eject vehicle to align the eject vehicle along an updated intercept vector;

determining at least one of acceleration, velocity, and position information in at least an angular coordinate of the eject vehicle with an inertial management unit; and

performing a Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) to determine a roll estimation by synthesizing information from two orthogonal linearly polarized receive antennas and information from the inertial management unit.

**17**. The method of claim **16**, wherein performing the JAPRAE further comprises determining the roll estimation with an extended Kalman filter.

**18**. An active protection system for an aerial platform, comprising:

an onboard system on an aerial platform comprising one or more sensor modules, the onboard system configured to:

detect a plurality of aerial vehicles within a threat range of the aerial platform;

determine if any of the plurality of aerial vehicles is an aerial threat;

determine an intercept vector to the aerial threat, the intercept vector pointed toward a projected interception point of an identified aerial threat;

communicate with at least one eject vehicle responsive to determining the intercept vector; and

the at least one eject vehicle configured to be ejected from the aerial platform, the at least one eject vehicle comprising:

a plurality of pitch thrusters configured to adjust a pitch of the at least one eject vehicle relative to the intercept vector to rotate a longitudinal axis of the at least one eject vehicle to substantially align with an intercept vector; and

a rocket motor configured to accelerate the at least one eject vehicle along the longitudinal axis of the at least one eject vehicle; and

one or more divert thrusters configured to divert the at least one eject vehicle in a direction substantially perpendicular to the longitudinal axis of the at least one eject vehicle.

**19**. The active protection system of claim **18**, wherein:

the onboard system is further configured to:

track the at least one eject vehicle as it moves along the intercept vector;

determine a diversion vector in a direction substantially perpendicular to a travel direction of the at least one eject vehicle; and

communicate a divert command to the at least one eject vehicle responsive to determining the diversion vector; and

the at least one eject vehicle is further configured to activate at least one of the one or more divert thrusters responsive to the divert command.

**20**. The active protection system of claim **18**, wherein the at least one eject vehicle further comprises a plurality of attitude control thrusters positioned near a front of the at least one eject vehicle and configured to make adjustments to an attitude of the at least one eject vehicle when activated.

**21**. The active protection system of claim **20**, wherein the at least one eject vehicle further comprises an electronics module configured for performing an attitude control algorithm to use a determination of a roll estimation of the at least one eject vehicle to determine an appropriate time to fire an attitude control thruster of the plurality of attitude control thrusters to adjust the attitude of the at least one eject vehicle to a desired orientation.

**22**. The active protection system of claim **18**, wherein the at least one eject vehicle further comprises two orthogonal linearly polarized receive antennas to match incoming polarization of received signals to substantially eliminate polarization mismatch loss induced by body rotation of the at least one eject vehicle.

**23**. The active protection system of claim **22**, wherein the at least one eject vehicle further comprises an inertial management unit configured to determine at least one of acceleration, velocity, and position information in at least an angular coordinate of the at least one eject vehicle responsive to one or more sensors selected from the group consisting of accelerometers, gyros, and magnetometers.

**24**. The active protection system of claim **23**, wherein the at least one eject vehicle further comprises an electronics module for performing a Joint Adaptive Polarization and Roll Angle Estimator (JAPRAE) configured to determine a roll estimation by synthesizing information from the two orthogonal linearly polarized receive antennas and information from the inertial management unit.

**25**. The active protection system of claim **24**, wherein the JAPRAE is configured to determine the roll estimation using an extended Kalman filter.

**26**. The active protection system of claim **18**, wherein the onboard system is configured to communicate directional coordinates of the intercept vector to the at least one eject vehicle.

**27**. The active protection system of claim **18**, wherein the onboard system is configured to communicate pitch commands derived from the intercept vector to the at least one eject vehicle.

**28**. The active protection system of claim **18**, wherein the onboard system is configured to communicate information associated with the intercept vector to the at least one eject vehicle at least one of before ejection or after ejection of the at least one eject vehicle.

**29**. An eject vehicle for disposition in a dispenser of an active protection system, comprising:

an airframe shell containing a warhead;

a nose portion attached to the airframe shell;

a rocket motor removably attached to the airframe shell and configured to accelerate the eject vehicle along an intercept vector and to detach from the airframe shell upon exhaustion; and

a plurality of attitude control thrusters attached to the nose portion of the eject vehicle and configured to rotate a longitudinal axis of the eject vehicle about an axis orthogonal to the longitudinal axis of the eject vehicle,

wherein each attitude control thruster of the plurality of attitude control thrusters is configured to rotate the longitudinal axis of the eject vehicle a first amount within a first range of angles while the rocket motor is attached to the airframe shell, and

wherein each attitude control thruster of the plurality of attitude control thrusters is configured to rotate the longitudinal axis of the eject vehicle a second amount within a second different range of angles after the rocket motor has detached from the airframe shell.

**30**. The eject vehicle of claim **29**, wherein the plurality of attitude control thrusters comprises a plurality of microthrusters.

**31**. The eject vehicle of claim **29**, wherein the plurality of attitude control thrusters is configured to adjust a velocity vector of the eject vehicle.

**32**. An active protection system for a platform, comprising:

at least one eject vehicle for disposition in a dispenser on the platform, the at least one eject vehicle comprising:

an airframe shell containing a warhead;

a nose portion attached to the airframe shell and including a plurality of thrusters for controlling a pitch and attitude of the at least one eject vehicle; and a rocket motor attached to the airframe shell and configured to accelerate the at least one eject vehicle along an intercept vector upon launch from the dispenser; and

a computing system in communication with at least one engagement management module onboard the platform and the at least one eject vehicle, the at least one engagement management module configured to detect an aerial vehicle within a threat range of the platform, wherein the computing system is configured to:

determine if the aerial vehicle is an aerial threat;

transmit a launch command to at least one eject vehicle to be launched from the platform to intercept a determined aerial threat; and

transmit guidance commands to the at least one eject vehicle while the at least one eject vehicle is in flight along the intercept vector for intercepting the determined aerial threat, and

wherein the computing system includes at least one thruster module configured to control ignition and use of the plurality of thrusters of the at least one eject vehicle in order to maintain thrust for the at least one eject vehicle throughout an intercept operation.

**33**. The active protection system of claim **32**, wherein the computing system is configured to maintain a count of which thrusters of the plurality of thrusters have already been fired and a count of which thrusters of the plurality of thrusters remain available to fire.

**34**. The active protection system of claim **32**, wherein the plurality of thrusters comprises a plurality of attitude control thrusters configured to maintain an angle of attack of the eject vehicle while the eject vehicle is in flight toward the interception point.

**35**. The active protection system of claim **32**, wherein the plurality of thrusters comprises a plurality of divert thrusters configured to divert the eject vehicle in a direction at least substantially perpendicular to the intercept vector.

**36**. The active protection system of claim **32**, wherein the plurality of thrusters comprises a plurality of pitch thrusters configured to rotate a longitudinal axis of the at least one eject vehicle to substantially align the longitudinal axis of the at least one eject vehicle with the intercept vector.

**37**. The active protection system of claim **32**, further comprising a plurality of micro-thrusters attached to the nose portion of the at least one eject vehicle.

**38**. The active protection system of claim **32**, wherein the computing system is configured to determine how many thrusters of the plurality of thrusters are required to intercept the determined aerial threat based on a remaining total mass of the at least one eject vehicle, a center of gravity location of the at least one eject vehicle, and an inertia tensor of the at least one eject vehicle.

**39**. The active protection system of claim **32**, wherein the computing system is configured to update a remaining total mass of the at least one eject vehicle, a center of gravity location of the eject vehicle, and an inertia tensor of the at least one eject vehicle as the plurality of thrusters is fired.

**40**. The active protection system of claim **32**, wherein the computing system is configured to determine a closest point of approach of the at least one eject vehicle and the determined aerial threat and to transmit a detonation command to the at least one eject vehicle to detonate when the at least one eject vehicle reaches the closest point of approach.

**41**. An eject vehicle for disposition in a dispenser of an active protection system, comprising:

an airframe shell containing a warhead, the airframe shell comprising:

a plurality of attitude control thrusters configured to maintain an angle of attack of the eject vehicle throughout an intercept operation;

a plurality of pitch thrusters configured to rotate a longitudinal axis of the eject vehicle to at least substantially align the longitudinal axis of the eject vehicle with an intercept vector; and

a plurality of divert thrusters configured to divert the eject vehicle in a direction at least substantially perpendicular to the intercept vector; and

a rocket motor removably attached to the airframe shell and configured to accelerate the eject vehicle along the intercept vector upon launch from the dispenser.

**42**. The eject vehicle of claim **41**, wherein the plurality of attitude control thrusters is positioned forward or aft of a center of mass of the eject vehicle and oriented to generate a force on the eject vehicle at least substantially perpendicular to the longitudinal axis of the eject vehicle.

**43**. The eject vehicle of claim **41**, wherein the plurality of pitch thrusters is positioned offset from a center of mass of the eject vehicle and oriented to generate a force on the eject vehicle at least substantially perpendicular to the longitudinal axis of the eject vehicle.

**44**. The eject vehicle of claim **41**, wherein the plurality of divert thrusters is positioned proximate a center of mass of the eject vehicle and oriented to generate a force on the eject vehicle at least substantially perpendicular to the longitudinal axis of the eject vehicle.

**45**. The eject vehicle of claim **41**, wherein the plurality of attitude control thrusters and the plurality of pitch thrusters are positioned proximate a nose portion of the eject vehicle.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

# CERTIFICATE OF CORRECTION



PATENT NO. : 9,551,552 B2
APPLICATION NO. : 13/839637
DATED : January 24, 2017
INVENTOR(S) : James Kolanek et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification

| | | |
|---|---|---|
| Column 11, | Line 48, | change "system"." to --system."-- |
| Column 17, | Line 67, | change "acceleration a, and" to --acceleration $\mathbf{a}_{KV}$, and-- |
| Column 19, | Line 9, | change equation reference number at right margin from "(3)" to --(5)-- |
| Column 19, | Line 16, | change equation reference number at right margin from "(4)" to --(6)-- |
| Column 19, | Line 22, | change "equation (4) the" to --equation (6) the-- |
| Column 19, | Line 30, | change equation reference number at right margin from "(5)" to --(7)-- |
| Column 20, | Line 3, | change equation reference number at right margin from "(6)" to --(11)-- |
| Column 20, | Line 45, | change equation reference number at right margin from "(7)" to --(14)-- |
| Column 21, | Line 20, | change equation reference number at right margin from "(8)" to --(19)-- |
| Column 23, | Line 67, | change equation reference number at right margin from "(9)" to --(30)-- |
| Column 24, | Line 39, | change "Q is dynamic" to --*Q* is dynamic-- |
| Column 24, | Line 40, | change "S is reference" to --*S* is reference-- |
| Column 24, | Line 41, | change "d is reference" to --*d* is reference-- |
| Column 24, | Line 42, | change "$\mathrm{C}_m$ is total" to --$C_m$ is reference-- |
| Column 24, | Line 43, | change "$\mathrm{C}_n$ is total yawing moment coefficient)" to --$C_n$ is total yawing moment coefficient-- |
| Column 24, | Line 44, | change "$\bar{\mathrm{X}}_{CP}$ is normalized" to --$\bar{X}_{CP}$ is normalized-- |
| Column 24, | Line 46, | change "$\bar{\mathrm{X}}_{CG}$ is normalized" to --$\bar{X}_{CG}$ is normalized-- |

Signed and Sealed this
Ninth Day of January, 2018

Joseph Matal

*Performing the Functions and Duties of the*
*Under Secretary of Commerce for Intellectual Property and*
*Director of the United States Patent and Trademark Office*

| | | | |
|---|---|---|---|
| | Column 24, | Line 48, | change "$\bar{\mathrm{Y}}_{CG}$ is CG offset" to --$\bar{Y}_{CG}$ is CG offset-- |
| | Column 24, | Line 49, | change "$\bar{Z}_{CG}$ is CG offset" to --$\bar{Z}_{CG}$ is CG offset-- |
| | Column 24, | Line 50, | change "$\mathrm{C}_A$ is axial drag-force" to --$C_A$ is axial drag-force-- |
| | Column 24, | Line 51, | change "$\mathrm{C}_N$ is normal force" to --$C_N$ is normal force-- |
| | Column 24, | Line 52, | change "$\mathrm{C}_Y$ is lateral force" to --$C_Y$ is lateral force-- |
| | Column 24, | Line 53, | change "$\mathrm{C}_{m_q}$ is pitch damping" to --$C_{m_q}$ is pitch damping-- |
| | Column 24, | Line 54, | change "$\mathrm{C}_{n_r}$ yaw damping" to --$C_{n_r}$ is yaw damping-- |
| | Column 24, | Line 55, | change "$\bar{\mathrm{q}}$ is normalized" to --$\bar{q}$ is normalized-- |
| | Column 24, | Line 56, | change "$\bar{\mathrm{r}}$ is normalized" to --$\bar{r}$ is normalized-- |
| | Column 25, | Line 48, | change "force F pushes" to --force $F$ pushes-- |

In the Claims

| | | | |
|---|---|---|---|
| Claim 13, | Column 28, | Line 35, | change "comprising making" to --comprising making small-- |